THE MORPHOLOGY OF WIND FLOW AND BUILT FORM

A Development of Design Oriented Measures of Wind in Relation to the Environmental Aspects of Wind Flow in Built Form

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SUMMARY

This thesis is an attempt to develop measures of wind that are related to the design of built form. On account of their theoretical nature, descriptions of flow in fluid dynamics are unsuitable in relation to the design problem. Here, the measures are identified as the exposure, the non-uniformity and the spatial distribution of the exposure. Through an extensive experimental programme, these aspects of flow were computed for simple model arrangements. To select the most suitable measure, a number of formulations were used in the computations, and the most appropriate measure was selected, according to criteria of economy of data, independence of sample size and sensitivity to change in form. The selected formulations for each of the three measures were transformed into their counterparts and combined in the synthesis of an Environmental Wind Index. The Index could prove of great value in the morphological study of wind flow and built form on account of its comprehensive yet concise formulation; the Index is also potentially of great value in design on an evaluative approach or a form-generative one. The development of the Environmental Wind Index made it convenient to use a simple two-dimensional plane of measurements, but its application in real design situations is also considered. Two methodological models of design with wind are suggested.

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THE MORPHOLOGY OF WIND FLOW AND BUILT FORM

A GENERAL INTRODUCTION

THE CONTEXT

Architecture operates on two systems: a natural system which is defined by the laws of nature governing objects within their domain; and a human system which embraces human values, the ways human beings organise themselves and their physiological, perceptual and psychological faculties. A function of architecture can be regarded as to achieve a match between a desired human need and one or more elements of the natural system. Wind is such an element of the natural system on which architecture operates. The human requirement of enhancing the beneficial effects of wind and subduing its undesirable aspects is a familiar theme of architectural form in the building culture of many societies. The integration of this and other aspects of the natural environment in such built forms is the result of generations of design culture which does not seem to have a parallel in modern design. Due to the growing complexities of the problems of modern design, many design aspects had to be externalised and isolated for their proper treatment and introduction in a form-generative situation. This has proved of great practical value in such aspects as lighting and the accoustical and thermal properties of built form. By contrast, the wind aspects of built form lagged far behind. There may be many reasons for this; one reason, however, is the absence of appropriate measure of wind in relation to built form.

The knowledge of wind in terms of its basic mechanics and governing laws has, so far, been contributed to, largely, by meteorologists and aerodynamicists (chapter I). The contribution of the former has helped in greater

understanding and prediction of its behaviour on both a global and a local scale. The latter have acquired a knowledge of wind in relation to its interaction with moving bodies, e.g., aircraft. Both fields have approached and identified the phenomenon of wind, justifiably, in a manner that best serves their purposes. In the field of design of built form the phenomenon of wind acquires a totally different context as a result of the interaction of the natural system (wind) and a man-made system (built form) with characteristic physical expressions, and man's needs which have to be satisfied for his well-being in a built form influenced by its constant immersion in the natural wind field. This calls for a completely different formulation of research in relation to wind. This new formulation should be guided by our conceptions as designers and users of built form as to which aspects of the wind are discernible as a result of its interaction with built form and relevant to the general objective of comfort and well-being in it. It is, therefore, of fundamental importance that design-oriented measures of wind should be developed to help bridge the gap in the design of built form from an environmental as distinct from a structural viewpoint. This thesis is concerned with the development of such measures.

THE MORPHOLOGICAL PERSPECTIVE

The word morphology was first introduced by Goethe in 1827. In biology, it connotes the study of form in organisms. Goethe regarded plants as variants of an 'archetypical' form where the 'Upflanze' is constituted by an axial structure bearing lateral appendages (respectively, the stem and the leaves). In time, the development of the organism (plant) was regarded as a reiteration of successive parts leading to modifications of the fundamental repetitive unit. Wardlaw[99] argues that "every living plant is a complex organisation in which many factors, extrinsic and

intrinsic are involved. It is a unique physical system, holistic and harmonious in its development. Because this is so, it is not enough to give a factorial account of the numerous processes that take place during the individual development. There must be a synthesis if our understanding of plants as organisms is to advance. For those who entertain this concept, it appears that morphology - which is concerned with the visible manifestation of specific developmental processes, and the factors involved in them - must continue to occupy a central position in botanical science." From this, it can be deduced that the concept of morphology rests on two things:

a) the existence of a wide range of apparently undifferentiated processes, characteristics or operators pertaining to a certain entity or phenomenon or classes of entities or phenomenon.

b) the need to identify, or isolate, and describe strands of properties that are ever-present and independent of change and development in the processes, characteristics or operators that qualify such entities or phenomena.

The morphological concept has provided those concerned with method in the design field with a potentially useful basis of a design method. Jones[22] describes such a method as 'Morphological Charts' and states its aim as the widening of the area of search for solutions to design problems. It is outlined by three points:

1. defining the functions that any acceptable design must be able to perform.
2. listing, on a chart, a wide range of subsolutions, i.e., alternative means of performing each function.
3. selecting an acceptable set of subsolutions, one for each function.

The objective of a morphological chart is to 'force divergent thinking and to safeguard against overlooking novel solutions to a design problem.' The method however, has a main difficulty in identifying a set of functions that are:

a) essential to any solution.

b) independent of each other.

c) inclusive of all parts of the problem.

d) few enough in number to produce a matrix that can be searched in a short time.

There exists, however, a subtle but fundamental methodological differente in the use of the morphological concept in the natural sciences and in the design field. In the former, one is concerned with an already existing field of processes, characteristics or operators due to nature. In design, such a field has to be initially generated, before subsequent synthesis (to use Wardlaw's term) is attempted.

'The Morphology of Wind Flow and Built Form' is carefully aimed at the generation of a wide area of search for the appropriate description of wind aspects that are relevant to the environmental aspects of built form. This wide area of search is narrowed by the gradual introduction of appropriate criteria converging towards a manageable size of mutually relevant aspects of wind and form and their relationships. Therefore, it is possible to identify three components of the morphology of wind flow and built form:

a) the morphology of the ever-present aspects of wind in a built form.

b) the morphology of the ever-present aspects of built form in relation to wind.

c) the morphology of the nature of the relationship between the two sets of aspects.

This division of the morphology of wind flow and built form assumes only a

methodological convenience, since the study of any of the three necessarily leads to the inclusion of the remaining two, at least partly.

THE CHOICE OF THE MEASURES (SOME DESIGN-RELEVANT ASPECTS OF WIND)

The search for meaningful relations between wind and built form as pursued in this thesis is based on two concepts. The first is to designate the relevant aspects of the phenomena of wind in the context of design of built form. The second is to articulate these aspects by assigning to them appropriate descriptors or measures. An important criterion in the choice of both the relevant aspects of wind and their measures is their apparent correlation with experiential aspects concerning the users of built form. In the designation of the relevant aspects of wind in the design context of built form the author has drawn on his own experience as to what designers would like to know about the wind conditions in the development of their designs*. Such knowledge about the wind conditions seems to be vital in the process of decision-making, both in comparative and performance evaluative contexts. It is felt that it is important, if such design decision-making is to be improved, that the designer should have a good estimation of the exposure conditions of the space under investigation. Since such a knowledge of the exposure can only give an average property, it is essential, to form a clearer idea about wind conditions, to study their variations relative to the average property expressed by the exposure. Further, wind in relation to built form has certain and important spatial regularities. Plotting of exposure against distance from the wall of a building, for example, reveals a characteristic profile of the exposure, depending on the

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*With Professor C.B. Wilson of the Department of Architecture of Edinburgh University, the author was involved in exploratory studies of wind movement in housing layouts of a large-scale housing project.

geometry of the building, its orientation and its spatial relationship with other buildings. Such an aspect of the relationship between wind and built form has important implications in detecting the spatial distribution of the exposure within the space under investigation.

These aspects of wind in relation to built form, can be articulated on a numerical scale the values of which are computed from certain formulae (measures) after a comparative study in depth to select a good measure for each of the aspects.

In addition to the quantifiable aspects of the wind-form interaction, it is also realised that a useful medium of expressing the relationships, especially in exploratory studies, would be a visual medium with a quantitative component. This is best achieved in the expedient method of plotting speed contours which give an initial general impression of the flow patterns and the prevailing range of speed values.

THE MEASURES

It is suggested that in the design of built form four measures of air movement are pertinent. These are:

a) a quantitative visual description of flow.

b) a measure of exposure.

c) a measure of non-uniformity.

d) a measure to describe change in exposure on a continuous spatial scale within, or in the environs of, a built form.

These measures are developed in chapters III, IV, V and VI respectively. Measure (a) is a pictorial representation of the flow given by plotting its speed contours from grid measurements. In developing this measure, attention was given to the unfolding of the patterns as a result of a linked progression of form aspects and direction of flow. The problem of coping

with a vast body of information which characterises this measure is also considered and a way of representing and contracting it is suggested. This is expressed in a morphology of form-flow patterns.

The development of a measure of exposure is based on a search among seven possible measures. The criteria on which the appropriate measure is selected are those of minimal data needs, structure of data and sensitivity to change in form. It takes values from 0 to 1, where 1 is the initial exposure without the building.

The non-uniformity measure describes local deviations from the generalised measure of exposure. It is also developed through a search among possible measures, using the same criteria as in the case of the exposure measure. It is expressed as a percentage of the exposure measure.

The spatial variation of the expsoure is described by a measure of exposure profile across space. Local exposures of consecutive zones are computed and plotted against the positions of their zones within the relevant space. A localisation factor is formulated and computed as a shape index of the exposure profile. The most important attribute of this measure is its comparative nature between different forms. In this work, this aspect necessitated the development of a topological description of the space in which a common attribute of spaces with different dimensions is expressed.

The measures of exposure, non-uniformity and the localisation factor are transformed into their counterparts of shelter, uniformity and non-localisation and combined into a single general measure. This general measure is termed the Environmental Wind Index (chapter VII). The application of this index in design is discussed in chapter VIII.

Chapter IX is an attempt to formalise two design approaches in relation to design with wind in an urban context. The two design models take a limited range of form aspects, but it is shown that they are open to incorporate further wind relevant form aspects. They emphasise the importance of the

existence of a range of alternative forms satisfying pre-stated conditions of wind flow so that other design considerations are possible to introduce.

The relationship between form and flow can be a one-to-one type of relationship or it can be an algorithmic relationship. Measures (b), (c) and (d) can be used in the one-to-one type of form-flow relationships, but they can also have the added advantage, on account of the sensitivity criterion, of applicability in an algorithmic type of relationship.

Since these measures had to be developed using a form the investigations give some insight into the relationship between flow and some form aspects of the simple arrangements used (two parallel identical blocks changing their length, spacing and orientation). The vast number of arrangements was necessary from the point of view of development of the measures. It was necessary to cover as wide a range of arrangements as possible to avoid any possible local bias caused by a limited size range.

Close to the study of measures of flow is the study of the description of form. In chapter I a general review is given of the concepts of form description available in mathematical and statistical theory. The potential of these tools in describing form in relation to flow is emphasised, but no attempt is made to develop explicit measures of form in relation to flow. The literature on air flow studies in relation to form is scattered. A representative rather than a comprehensive review of it is given in chapter II, emphasising the main themes and approaches of air movement-built form studies.

Closing this introduction, it should be emphasised that a working knowledge of air flow-form relationships cannot be complete without considering these measures in conjunction. It should also be emphasised that the primary aim of this thesis is the development of measures of flow in relation to form rather than giving 'design values' for the forms necessarily used in

the investigations.

PRESENTATION

The thesis is divided into three main parts: Part I is concerned with the problem of description of flow and form; Part II is devoted to the development of individual measures of flow in relation to built form; and Part III considers the design application of the Environmental Wind Index and develops two methodological models for design with wind in an urban context. At the end of each chapter there is a conclusion, but general conclusions are given at the end of the thesis.

There are nine chapters. Each chapter is divided into sections and each section into paragraphs, all of which are numbered. Thus, the number 4.05 means section 4, paragraph 5. Diagrams are also numbered. Thus, diagram 4.o5 would mean diagram 5 of chapter IV.

A subject bibliography is also given.

PART I

THE PROBLEM OF DESCRIPTION

C H A P T E R I

THE PROBLEM OF DESCRIPTION:

MEASURES OF FLOW AND MEASURES OF FORM

1.00 INTRODUCTION

1.01 The objective of research in the interaction between built form and air movement is to establish relationships between the two which help designers to create better environments. To establish such relationships one has to consider the following problems:-

a) The aspects of air movement relevant to users and influenced by built form in the design context.

b) The aspects of built form relevant to air movement in the design context.

c) The nature of the relationships between air movement and built form.

1.02 A methodical approach may be founded on basic search for the interactive aspects of air movement and built form as a first step. Once these aspects are identified the next step becomes the search for relationships between them which are meaningful from the designer's point of view.

1.03 The major problem in any search for such relevant aspects of air movement and built form lies in the descriptive tools to be used, first, for specifying these relevant aspects and, secondly, for specifying the relationships between them. This will remain to be the fundamental problem in air flow-built form studies. Since the relationship between the two sets of aspects remains crucial to designers, the descriptive tool, in addition to its descriptivity of form or flow should be amenable to application in a relational context.

1.04 In this chapter some of the existing formalisms and the underlying concepts of flow and form description will be reviewed. Their

use, as descriptive tools for flow and form in a relational context will be assessed and suggestions will be made as to potential descriptive tools. This review, therefore, can be neither comprehensive nor far reaching in depth. It offers, however, some fundamental concepts in the description of flow and form as an initial field of choice for research in this vital area.

2.00 THE EQUATIONS OF CHANGE

2.01 The equations of change are statements of the conservation of mass, momentum, and energy. The study of flow at the macro level is mostly concerned with the fluid flow or transfer of momentum. In chemical engineering problems fluid flow plus heat transfer, diffusion and, sometimes, chemical kinetics are taken into consideration.

2.02 A fluid is made up of molecules with spaces between them. The study of fluid motion on a macro scale assumes that the fluid is continuous - a continuum. This is the beginning of many abstractions and assumptions, which are necessary to conveniently represent fluid motion. The study of fluid motion on a molecular level has also received great attention. The theory developed in that area is important in the study of rarefied gas dynamics.

2.03 In developing mathematical models for fluid flow two representations are introduced. The first is an integral form and the second is in the form of differential equations. The differential model is a series of differential equations with no general solution. In applying them a series of appropriate assumptions have to be made in order to arrive at analytical solutions. In many cases, however,

analytical solutions do not exist in which case resort can be made to numerical methods. Where analytical and numerical solutions cannot be obtained empirical analysis guided by the differential equations of the system, is necessary.[30]

2.04 In studying fluid flow there are two approaches: the Eulerian approach and the Lagrangian approach. The first notes the history of a point in a moving fluid while the second follows the motion of a particle in a moving fluid.

2.05 To describe a fluid flow five basic variables are needed: three velocity components and two thermodynamic properties (e.g. pressure, temperature, density, enthalpy, entropy). By specifying a velocity vector and two thermodynamic properties as functions of space and time a fluid flow is completely determined.

2.06 The five variables are used to develop five basic equations of flow: three components of the equation of motion, a continuity equation and an energy equation. The energy equation is sometimes written in terms of three variables (temperature, density and pressure) which requires the introduction of an equation of state making the numer of variables six in six equations.[33]

2.07 The development of the equations of fluid motion is based on four basic laws:

a) CONSERVATION OF MASS

b) NEWTON'S SECOND LAW OF MOTION

c) CONSERVATION OF ENERGY (THE FIRST LAW OF THERMODYNAMICS)

d) SECOND LAW OF THERMODYNAMICS.

Since these laws are only valid in a situation where the system under consideration maintains its identity while it undergoes change it

is important to define and identify the relevant system. Since it is not convenient to identify and follow fixed quantities of a moving fluid a field theoretic point of view is appropriate whereby a definite fixed region or volume in space is identified. This is called the control volume (c.v.) and the basic laws are applied to identify the properties of the fluid in the control volume at any given time regardless of the fact that the fluid is constantly changing, diagram 1.1.

2.08 Here, the basic equations of fluid motion in integral form, and later in differential form, are stated and derivations can be referred to.[33]

3.01 CONSERVATION OF MASS

The equation,

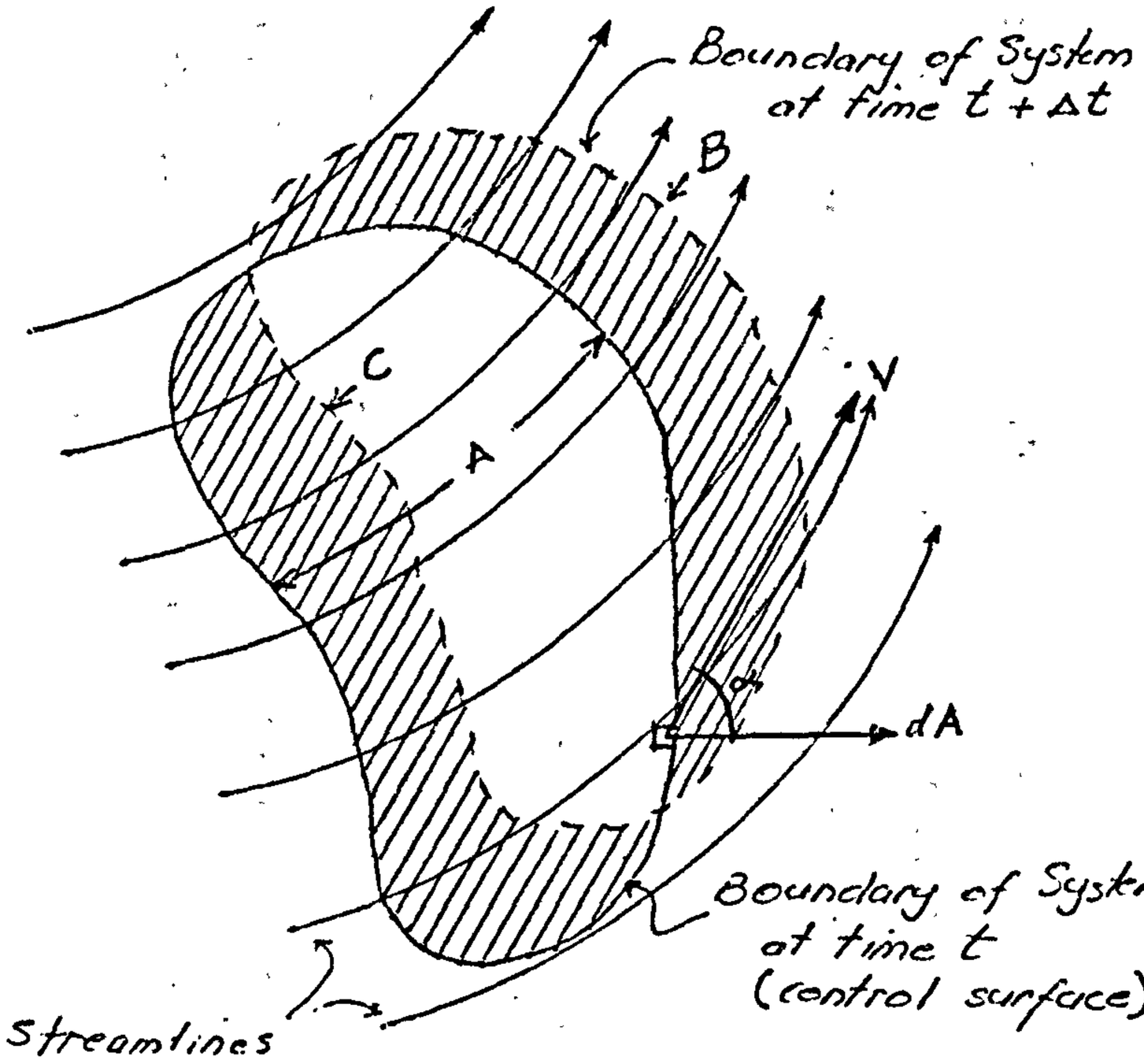
$$\int_{c.s.} \rho V.dA = -\frac{\partial}{\partial t} \int_{c.v.} \rho d\nu \qquad \ldots\ldots (1)$$

is the integral form of the continuity equation. c.s. is the control surface bounding the control volume c.v. V is the velocity vector. ρ is the density, ν is the volume. The physical meaning of the equation is that the net rate of mass flow of fluid through the control surface is equal to the time rate change in the mass of fluid inside the control volume.

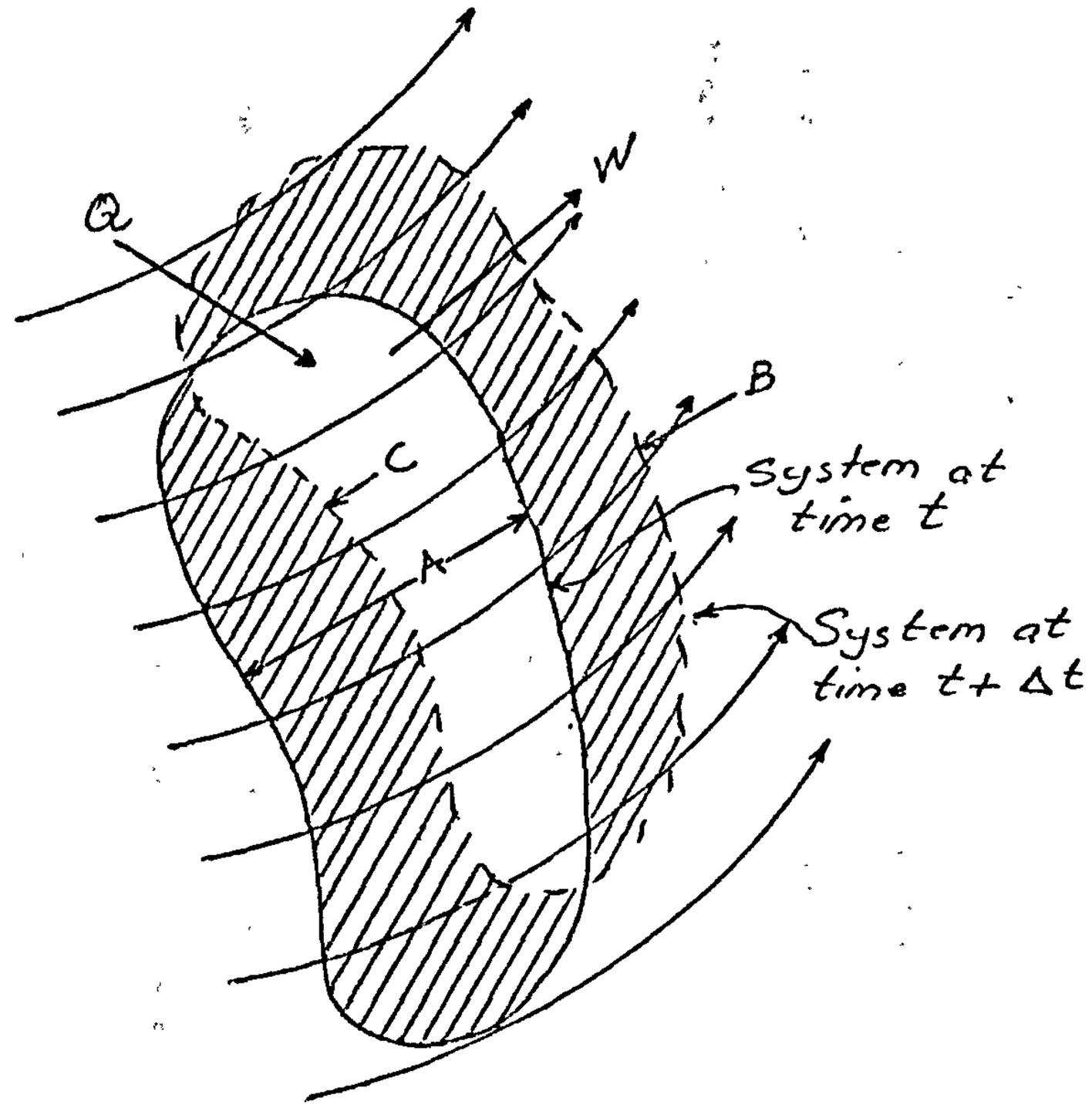
For a steady flow ($\frac{\partial \rho}{\partial t} = 0$) the right hand side of 1 is zero, since the control volume is fixed.

$$\therefore \quad \int_{c.s.} \rho V.dA = 0 \qquad \ldots\ldots (2)$$

and for incompressible flow, where ρ is constant



(a) System moving through a Control Volume.



(b) Control Volume for Energy Balance.

DIAGRAM 1.1

$$\int_{c.s.} V.dA = 0 \qquad \ldots\ldots (3)$$

3.02 MOMENTUM

The momentum equation of fluid motion is basic to the study of forces of fluids on solid surfaces or fluids. It is based on Newton's second law,

$$F = \frac{dM}{dt} \qquad \ldots\ldots (4)$$

where F is a force acting on a particle or a system of particles of fixed mass, M is the total linear momentum of the system.

The integral form of the momentum equation of fluid flow is,

$$F = \frac{\partial}{\partial t} \int_{c.v.} V\rho d\nu + \int_{c.s.} V\rho V.dA \qquad \ldots\ldots (5)$$

The total force F is the sum of the surface force F_s due to pressure and shear forces, and a body force, B which is a force per unit volume. Therefore the momentum equation for the control volume can be written as

$$F_s + \int_{c.v.} Bd\nu = \frac{\partial}{\partial t} \int_{c.v.} V\rho d\nu + \int_{c.s.} V\rho V.dA \qquad \ldots\ldots (6)$$

Physically, the equation states that the forces in the control volume are equal to the time rate of change of momentum in the control volume plus the momentum rate of flow through the control surface. The validity of this equation is limited by the condition of no acceleration according to the original formulation of Newton's laws. For steady flow and negligible body forces the equation becomes

$$F_s = \int_{c.s.} V\rho V.dA \qquad \ldots\ldots (7)$$

3.03 ANGULAR MOMENTUM

The momentum equation

$$F_s + \int_{c.v.} B d\nu = \frac{\partial}{\partial t} \int_{c.v.} V\rho d\nu + \int_{c.s.} V\rho V.dA \qquad \ldots\ldots (6)$$

can be transformed into the equation of angular momentum if the vector of each term is taken as the cross product of the position vector r. Thus the equation of the angular momentum is

$$\int_{c.s.} r\times dF_s + \int_{c.v.} r\times B d\nu = \frac{\partial}{\partial t} \int_{c.v.} r\times V\rho d\nu + \int_{c.s.} r\times V\rho V.dA \quad \ldots (8)$$

Interpreting the physical meaning of this equation the integrand of $r\times dF_s$ gives the moment of the force dF_s at the control surface taken around the origin. The integrand on the second term on the left gives the moment around the origin of the body forces due to an infinitesmal volume $d\nu$ in the control surface. The first term on the right is the integrand which gives the angular momentum of an infinitesmal mass element $\rho d\nu$, while the integration gives the total angular momentum of the mass due to the control volume. The second term is the rate of efflux of angular momentum through the control surface.

3.04 THE ENERGY EQUATION

The first law of thermodynamics can be stated, for a given system, as

$$Q - W = \Delta E \qquad \ldots\ldots (9)$$

where Q is the heat added to the system, W, work done by the system abd ΔE is the change in energy of the system.

In this equation heat and work are the result of interaction of the system considered with other systems. Energy is associated with the mass of the system. The energy of the system has three components: , internal energy resulting from molecular and atomic behaviour, kinetic energy and potential energy associated with the location of the system in the earth's gravitational field.

The integral form of the energy equation, derived for the control volume, is

$$\frac{dQ}{dt} - \frac{dW_s}{dt} = \frac{\partial}{\partial t}\int_{c.v.} e\rho d\nu + \int_{c.s.}(e+p/\rho)\rho V.dA \quad \ldots\ldots (10)$$

where $\frac{dW_s}{dt}$ is the time rate of work for all work except flow work. The letter e is the energy associated with a unit mass.

The physical interpretation of the energy equation is that the time rate of heat added to the system minus the work done by the system (other than flow work) is equal to the time rate of change of the stored energy in the control volume plus the net rate of the efflux of stored energy and flow work out of the control volume.

In the energy equation e is

$$e = u + \tfrac{1}{2}v^2 + g^2 \quad \ldots\ldots (11)$$

where u is the internal energy, v is the kinetic energy and g^2 is the potential energy, all with respect to unit mass.

3.05 THE SECOND LAW OF THERMODYNAMICS

The second law of thermodynamics for the given system is

$$dS - \frac{dQ}{T} \geq 0 \qquad \ldots\ldots (12)$$

where S is the entropy of the system, Q is the heat added to the system, T is the temperature of the system. It states that the entropy change, minus heat transferred to the system divided by the temperature is equal to or greater than zero.

The integral control volume form of the second law is

$$\frac{\partial}{\partial t}\int_{c.v.} s\rho d\nu + \int_{c.s.} s\rho V.dA - \int_{c.s.} \frac{q}{T} . dA \geq 0 \qquad \ldots\ldots (13)$$

q is the heat flux vector which is the rate of heat transfer per unit area, s is the specific entropy or entropy per unit mass.

4.00 THE DIFFERENTIAL EQUATIONS OF FLUID FLOW

4.01 The derivation of the differential equations of flow can be referred to in[30] but here they will only be stated.

4.02 The reference system is Eularian coordinates which apply to points in space and time rather than the location of individual particles. So the reference system is associated with the study of properties and velocity of the fluid as a function of position and time.

4.03 CONTINUITY

The equation of continuity in cartesian coordinates is

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial y}(\rho v) + \frac{\partial}{\partial z}(\rho w) = 0 \qquad \ldots\ldots (14)$$

where ρ is the density and u, v, w are the velocity components in the x, y, and z directions respectively.

For incompressible flow (ρ is constant) the continuity equation is

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \qquad \ldots\ldots (15)$$

In cartesian tensor notion the continuity equation is

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \qquad \ldots\ldots (16)$$

4.04 MOMENTUM EQUATION

In cartesian coordinates the components of the momentum equation in the x, y and z directions are respectively:

$$\rho \frac{Du}{Dt} = \rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}\right) \qquad \ldots\ldots (17a)$$

$$\rho \frac{Dv}{Dt} = \rho\left(\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z}\right) \qquad \ldots\ldots (17b)$$

$$\rho \frac{Dw}{Dt} = \rho\left(\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z}\right) \qquad \ldots\ldots (17c)$$

This can be written in tensor notation,

$$a = \frac{\partial \sigma_{11}}{\partial x} + \frac{\partial \sigma_{12}}{\partial y} + \frac{\partial \sigma_{13}}{\partial z} + B_x \qquad \ldots\ldots (18a)$$

$$b = \frac{\partial \sigma_{21}}{\partial x} + \frac{\partial \sigma_{22}}{\partial y} + \frac{\partial \sigma_{23}}{\partial z} + B_y \qquad \ldots\ldots (18b)$$

$$c = \frac{\partial \sigma_{31}}{\partial x} + \frac{\partial \sigma_{32}}{\partial y} + \frac{\partial \sigma_{33}}{\partial z} + B_z \qquad \ldots\ldots (18c)$$

In cartesian tensor notation the components of the momentum equation can be written conveniently as

$$\rho \frac{Dui}{Dt} = \rho\left(\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j}\right) = \frac{\partial \sigma_{ij}}{\partial x_j} + B_i \qquad \ldots\ldots (19)$$

$\rho \frac{Dui}{Dt}$ are the acceleration terms, $\frac{\partial}{\partial t}$ indicates a change with time at a fixed point in space. The other terms are known as convective acceleration (acceleration due to change in area of fluid path), terms usually appearing when Eulearian coordinates are used. The D/Dt operator is called the substantial or material derivative.

In vector form equations can be written as

$$\frac{DV}{Dt} = \frac{\partial V}{\partial t} + (V.\nabla)V = \frac{\partial V}{\partial t} + \nabla(V^2/2) - V \times \nabla \times V \qquad \ldots\ldots (20)$$

5.00 EULER'S EQUATIONS FOR FRICTIONLESS FLOW

5.01 Shear stresses are absent in frictionless flow. Normal stresses are due to the pressure which is isotropic. The general vector form of Euler's equations for frictionless flow are

$$\rho\left[\frac{\partial V}{\partial t} + \nabla(V^2/2) - V \times \nabla \times V\right] = -\nabla\rho + B \qquad \ldots\ldots (21)$$

where B is the body forces.

An important integral of Euler's equation is the generalised

Bernoulli or Euler equation

$$\frac{V_2^2-V_1^2}{2} + \int_1^2 \frac{d\rho}{\rho} + g(z_2-z_1) = 0 \qquad \ldots\ldots (22)$$

For steady state and gravitation potential indicated by $g(z_2-z_1)$. V_1, V_2 are velocities at two points 1, 2.

For incompressible flow

$$\frac{V_2^2-V_1^2}{2} + \frac{P_2-P_1}{\rho} + g(z_2-z_1) = 0 \qquad \ldots\ldots (23)$$

which is known as Bernoulli's equation for steady frictionless incompressible flow. Gravity is the only body force and the equation holds along a stream line.

DESCRIPTION OF WIND

(THE METEOROLOGIST APPROACH TO FLOW DESCRIPTION)

6.01 To describe the observed stae of the wind field rationally is a cumbersome task and in some circumstances extremely difficult. The reasons behind this are many[70] One difficulty is due to the mathematical structure of the equations of motion. These are statements of the wind motion which can only be solved within a range of simplifying assumptions. The assumptions needed render the solutions of little or no value as a valid statement about the state of the observed wind field. A second problem pertains to the wind flow mechanism which is unsteady and operates in a succession of gusts and lulls for short durations. The wind observations can be considered as highly modified by local conditions when they are taken within the

friction layer. The friction layer is near the earth's surface and in it the wind behaviour varies rapidly with height. When observations are made in the free atmosphere using balloons, calculations are equally inaccurate since they are made on the assumption that the rate of assent of the balloon is constant and that there are no vertical air currents . These factors, together with relatively scanty observations, have lead meteorologists to study and predict wind by correlating its desired characteristics (speed and direction) with other physical variables of the atmosphere. e.g. pressure, temperature etc.

RELATIONS BETWEEN WIND AND OTHER ATMOSPHERIC VARIABLES

7.00 THE EQUATIONS OF AIR MOTION

7.01 These equations relate the acceleration of flowing air and the forces acting upon it. There are four forces acting on the air

a) Gravity

b) Hydrostatic Pressure

c) Friction

d) Deviating force due to the rotation of the earth.

7.02 With reference to a rectangular coordinate system (with the z-axis as the vertical axis) we have [70]

$$\frac{dv_x}{dt} + 2w(v_z \cos\phi - v_y \sin\phi) = -\frac{1}{\rho}\frac{\partial p}{\partial x} + K\frac{\partial^2 v_x}{\partial z^2} \quad \ldots\ldots (24)$$

$$\frac{dv_y}{dt} + 2wv_x \sin\phi = -\frac{1}{\rho}\frac{\partial p}{\partial y} + K\frac{\partial^2 v_y}{\partial z^2} \quad \ldots\ldots (25)$$

$$\frac{d\nu_z}{dt} - 2w\nu_x\cos\phi = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g \qquad \ldots\ldots (26)$$

where,

ν_x, ν_y, ν_z are the velocity components along the coordinate axes

w the angular velocity of the earth

ϕ is the latitude

ρ is the density of the air

p is the atmospheric pressure

g acceleration due to gravity

K coefficient of transfer.

7.03 The equations describe the time rate of change of the velocity in component form. Thus the acceleration of wind at a given region can be determined from a knowledge of the latitude, angular velocity of the earth, and such physical variables as the pressure and density of the air. The inclusion of the pressure terms in the equations is significant otherwise parcels of air would move independent of their neighbours.

7.04 The horizontal component of the wind acceleration is very small compared with gravitational effect. Therefore the left hand side terms of equation (26) are considered negligible. However, vertical velocity and accelerations are important in local convective currents but in the study of large scale systems they can be neglected. Therefore, denoting $2w \sin\phi$ by λ and neglecting ν_z and $\frac{d\nu_z}{dt}$ we may rewrite equations 24, 25, 26 as

$$\frac{d\nu_x}{dt} - \lambda\nu_y = -\frac{1}{\rho}\frac{\partial p}{dx} + K\frac{\partial^2\nu_x}{\partial z^2} \qquad \ldots\ldots (27)$$

$$\frac{d\nu_x}{dt} + \lambda\nu_x = -\frac{1}{\rho}\frac{\partial p}{\partial y} + K\frac{\partial^2 \nu_y}{\partial z^2} \qquad \ldots\ldots (28)$$

$$0 = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g \qquad \ldots\ldots (29)$$

7.05 So the basic equations of wind motion relate acceleration, $\frac{d\nu}{dt}$, rotational effects, $\lambda\nu$, and frictional effects, $K\frac{\partial^2\nu}{\partial z^2}$. The absence, presence or the excess of any of these properties is used to classify winds. There are three classifications based on a) negligible rotational and frictional effects, b) frictional effects exceeding the rotation and accelerational terms, and c) rotational terms far in excess of both accelerational and frictional terms. The pressure term is always important for the continuity in the movement of an air body so it is used to equate the dominant effect (frictional, rotational or accelerational in the classification system). According to this classification there are three cases:

a) When rotational and frictional terms are negligible. In this case

$$\frac{d\nu_x}{dt} - \lambda\nu_y = -\frac{1}{\rho}\frac{\partial p}{\partial x} + K\frac{\partial^2 \nu_x}{\partial z^2} \qquad \ldots\ldots (27)$$

and

$$\frac{d\nu_y}{dt} + \lambda\nu_x = -\frac{1}{\rho}\frac{\partial p}{\partial y} + K\frac{\partial^2 \nu_y}{\partial z^2} \qquad \ldots\ldots (28)$$

respectively become

$$\frac{d\nu_x}{dt} = -\frac{1}{\rho}\frac{\partial p}{\partial x} \qquad \ldots\ldots (30)$$

and

$$\frac{d\nu_y}{dt} = -\frac{1}{\rho}\frac{\partial p}{\partial y} \qquad \ldots\ldots (31)$$

or, in vector notation,

$$\frac{dv}{dt} = -\frac{1}{\rho}\nabla p \qquad \ldots\ldots (32)$$

Equation (32) implies that the acceleration coincides with the pressure gradient and therefore the wind blows normal to the isobars from high to low pressure. However, at high wind velocities the rotational term becomes important and tends to balance the pressure term. Although the accelerational wind (called the Eulerian Wind) component can thus be dominated by rotational effects, yet it is always considered as important in identifying the nature of a wind flow.

b) When frictional terms exceed the rotational and the accelerational terms the equations of motion (27) and (28) respectively become

$$K\frac{\partial^2 v_x}{\partial^2} = \frac{1}{\rho}\frac{\partial p}{\partial x} \qquad \ldots\ldots (33)$$

and
$$K\frac{\partial^2 v_y}{\partial z^2} = \frac{1}{\rho}\frac{\partial p}{\partial y} \qquad \ldots\ldots (34)$$

In this case the wind will blow along the pressure gradient since frictional effects counteract the steady increase in velocity. The characteristics of such winds are that they occur at very low altitudes, over a relatively small horizontal area and have short time durations. Land and sea breezes are an example of this type of effect.

c) When rotational terms are far in excess of both accelerational and frictional terms the equations of motion (27) and (28) respectively reduce to

$$-\lambda v_y = -\frac{1}{\rho}\frac{\partial p}{\partial x} \qquad \ldots\ldots (35)$$

and
$$\lambda v_x = \frac{1}{\rho}\frac{\partial p}{\partial y} \qquad \ldots\ldots (36)$$

In this case the pressure gradient is balanced by the deviation force due to earth's rotation. Winds with such effects are called geostrophic winds. An expression relating the velocity of the geostrophic wind and the horizontal pressure gradient is

$$\nu_{gs} = \frac{\partial p/\partial n}{\rho\lambda} \qquad \ldots\ldots (37)$$

where ν_{gs} is the geostrophic wind velocity

$\frac{\partial p}{\partial n}$ is the horizontal pressure gradient obtained from

$$\frac{\partial p}{\partial n} = \sqrt{(\frac{\partial p^2}{\partial x} + (\frac{\partial p}{\partial y})^2} \qquad \ldots\ldots (38)$$

so equation (37) can be written as

$$\nu_{gs} = \frac{\text{pressure gradient}}{\rho\lambda} = \frac{\partial p/\partial n}{\rho\lambda}$$

In vector notation the geostrophic wind is

$$\nu_{gs} = -\frac{1}{\rho\lambda} \nabla p \times k \qquad \ldots\ldots (39)$$

where k is a vertical unit vector.

The physical interpretation of equations (37) and (39) is that the geostrophic wind blows along the high pressure isobars to the right of the direction of motion in the northern hemisphere. The velocity is proportional to the distance between isobars. The assumption that the accelerational term is negligible in the derivation of (37) is valid only when the isobars are straight and parallel and the pressure gradient is steady.

d) The curvature of path in wind flow sustains a centrifugal acceleration. When frictional and accelerational terms are negligible except the centrifugal acceleration the motion of the air is balanced by forces due to:

1. Pressure gradient in the direction of low pressure normal to the isobars.
2. The deviating force normal to the direction of motion and to the right in the northern hemisphere.
3. The centrifugal force at right angles to the direction of motion.

The balance of the forces in this case produces the gradient wind. There are two types of gradient wind according to whether 1 and 2 are in the same or opposite directions. If they are in the same directions then we have anticyclonic curvature for which the gradient wind is

$$v_{gr} = \frac{\text{pressure gradient}}{\rho\lambda} + \frac{v_{gr}^2}{\lambda r} \qquad \begin{matrix}\text{anticyclonic}\\ \text{curvature}\end{matrix} \quad \ldots (40)$$

If the pressure gradient and the centrifugal force are in opposite direction we then have a cyclonic curvature and the gradient wind velocity is given by

$$v_{gr} = \frac{\text{pressure gradient}}{\rho\lambda} - \frac{v_{gr}^2}{\lambda r} \qquad \begin{matrix}\text{cyclonic}\\ \text{curvature}\end{matrix} \quad \ldots\ldots (41)$$

where v_{gr} is the gradient wind velocity and r is the radius of curvature of the path.

The physical meaning of (40) and (41) is that the balance of

the three forces: pressure gradient, deviating force and the centrifugal force is achieved only when the wind blows along the isobars. This suggests the characteristic feature in the gradient wind; that it has no radial component. When the isobars do not converge sharply or diverge widely the gradient wind is a good representation of the true wind flow. This condition is obtained above the friction layer. If the curvature of the path, however, is not too small the geostrophic wind is a good approximation of the true wind above the friction layer. This can be inferred from the relationship between v_{gr} and v_{gs} obtained by combining (37), (40) and (41)

$$v_{gr} - v_{gs} = \pm \frac{v_{gr}^2}{\lambda r} \quad \ldots\ldots (42)$$

The term $\frac{v_{gr}^2}{\lambda r}$ is called the cyclostrophic term. It is negligible in high and middle latitudes when r is so large. In low latitudes with λ very small the geostrophic component becomes negligible in comparison with the cyclostrophic one.

CONCLUSIONS ON FLOW DESCRIPTION

From the previous sections it is possible to identify two approaches in flow description: the first is highly theoretical and abstract. It is based on fundamental laws of mechanics and thermodynamics. The second (which is illustrated by the description of natural wind) is practical and even pragmatic in formulating analytical descriptions appropriate to and dictated by the nature of the system they are trying to describe taking into account its parametric limitations.

In the study of air movement in relation to built form both approaches are necessary. The theoretical approach is necessary because it provides the basic and broad outlines on which any further practical developments may be founded. This is a level where the desired properties of flow from the point of view of the user can be decided upon and represented in a theoretical model. Thus there may well be a case for such a model to express the thermodynamic properties of the flow in relation to a built form expected to be influenced by thermal exchanges - an aspect which air movement studies have so far neglected either on the belief that it is relatively unimportant or on account of the difficulty to simulate the thermal input and flow at the same time. This latter aspect illustrates the significance of the second approach. In cases where the flow property envisaged cannot be directly encapsulated or effectively simulated greater insight is required to characterize its association with the more explicit properties and study it, therefore, in terms of these associations. Such an approach has a lot to offer in a field so dependent on simulation but can only represent the processes involved in isolation.

At this stage in research in air movement in relation to built form it is vital to look into related fields and see what they can offer to the designer in terms of flow aspects and measures. Such an investigation, however, can enrich insight by revealing fundamental concepts and approaches but cannot give material readily applicable in the field of environmental design of built form. From the designers' point of view a number of aspects are extremely important if their decision making in design of built form is to be improved in this area. These aspects may bear some similarity to those looked for in fluid mechanics problems (e.g. flow patterns), but their

orientation and description are to be strictly geared to the designers' particular need and skill. The aspects whose measures are developed in this work (Chapters 3,4,5 and 6) are:

1. Quantitive visual flow representation.
2. Exposure of a given space within an arrangement of built forms.
3. Uniformity of the exposure within that given space.
4. Spatial distribution of the exposure within the given space.

Taken together these aspects are believed to portray a design oriented picture about the flow in a given built form or in a progressive link of built forms. The appropriate measures to be developed are of a pictorial, graphical and numerical nature presented in a format easily accessible to the designer. Such measures are distinct in content and format from the familar fluid mechanics measures of flow.

THE DESCRIPTION OF FORM*
(CONCEPTS FROM MATHEMATICAL AND STATISTICAL THEORY)

8.01 To clearly define the aspects of built form relevant from the point of view of air movement is a much easier task than choosing the appropriate tool for description. The problem can be made even more

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* 'The Geometry of Environment' by L. March and P. Steadman is an excellent reference illustrating and tracing the development of mathematically orientated form description ideas. (RIBA Publications Limited, 1971.)

difficult by the types of relationships we intend to establish between form aspects and flow aspects. A relationship between the two sets of aspects can be a relationship of correspondence, one-to-one, or it can be an algorithmic relationship. In the first type, one-to-one relationship, the description of form is fairly straight forward since, given its form aspects pictorially, numerically or otherwise, its corresponding flow properties are associated. The second type amounts to a functional interdependence in which the form aspects are to be expressed on a linked progressive scale best achieved numerically or in the form of a mathematical function (Chapter VII). Form descriptions can be developed for either type of relationships defining form aspects such as solid and void, relative openness or compactness, their spatial distribution, the profile of a given urban structure etc.

8.02 In the following sections some fundamental concepts of form descriptive tools are reviewed and, in conclusion, their applicability to air flow-built form studies is assessed. These concepts pertain to mathematical and statistical theory but do not include plane geometry whose tools are already known and in common use. It is the limitation, however, of plane geometry that invites looking into other areas with greater potential to provide the appropriate form descriptors in this context.

9.00 CONCEPTS FROM SET THEORY

9.01 A set can be defined as any collection of objects, quantities or operators.[63] Each individual object, quantity or operator is an element of the set. A set is sometimes called a class and the

elements of a set can be sets in themselves. If x is an element of the set X this is written as $x \in X$ and as $x \notin X$ if it is not a member.

If X and Y are sets such that all the elements of Y are also elements of X then Y is a subset of X, written as

$$Y \subset X$$

it is also stated as Y is contained in X, written as

$$X \supset Y \quad .$$

If

$$Y \subset X$$

and

$$Y \neq X$$

then Y is called a proper subset of X.

9.02 For any set X there is a unique set of which the elements are all the subsets of X and is called the power set of X.

9.03 For a set X in which each element x is specified with a property P(x) there is a unique subset of X consisting of those elements for which P(x) holds. This subset is denoted by

$$\{x \in X : P(x)\}.$$

For sets A, B and C, if

$$A \subset B$$

and

and

$$B \subset C$$

then

$$A \subset C$$

For sets A and B, if

$$A \subset B$$

and

$$B \subset A$$

then

$$A = B$$

9.04 Sets can be mapped on each other. The idea of mapping a set A on a set B is to assign for every element of A an element of B by a rule or an operation. Mappings are also referred to as transformations or functions.

9.05 A number of operations can be performed on sets. There are two main such operations: the union of sets and the intersection of sets. The union of two sets A and B is defined as the set of all elements belonging to either A or B or both. It is denoted by

$$A \cup B$$

The intersection of two sets, A and B, is the set of all those elements common to both sets and is denoted by

$$A \cap B$$

9.06 The complement of a set A is the set of elements which do not

belong to A but are part of a universal or overall set U. Thus the union of a set A and its complement $\acute{A}$ is U:

$$A \cup \acute{A} = U$$

$$(\acute{A}) = A$$

and $$A \cap \acute{A} = 0 \quad \text{(null or zero set)}$$

9.07 The difference between two sets is the set of elements which belong to one but not to the other. The difference between two sets A and B, denoted

$$A - B$$

is the set of elements which belongs to A but not to B.

9.08 For any three sets A, B and C and the universal set U the following rules are basic:

a) $\acute{U} = 0$ $\quad A \cap \acute{A} = 0$

$\acute{0} = U$ $\quad A \cup \acute{A} = U$ $\quad (\acute{A}) = A$

b) $A \cup A = A$ $\quad A \cap A = A$

c) $A \cup U = U$ $\quad A \cup 0 = A$ $\quad A - 0 = A$

$A \cap U = A$ $\quad A \cap 0 = 0$ $\quad A - A = 0$

d) $A \cap B = B \cap A$ $\quad A \cup B = B \cup A$ (Commutative laws)

e) $(A \cup B) \cup C = A \cup (B \cup C)$ $\quad (A \cap B) \cap C = A \cap (B \cap C)$ (Associative laws)

f) $A \cup (B \cap C) = (A \cup B) \cap (A \cup C)$
$A \cap (B \cup C) = (A \cap B) \cup (A \cap C)$] (Distributive laws)

9.09 Set theory is often thought of as a symbolism and has little to offer beyond neat notation, but it offers the basis of a form descriptive tool for rectangular forms using a coordinate reference system. The method is discussed by March and Steadman[45] who demonstrate its use to describe forms as one, two or three dimensional spatial entities. For this the operations of the union of sets and the intersection of sets were used. Conceiving forms as compounds of small rectangular and modular units, two dimensional shapes are thought of to be composed of 'quadrats' and three dimensional shapes of 'cubelets'. The idea is based on a way to name the quadrats or the cubelets and a way to say how they are combined to produce the form to be described. With reference to a modular grid in a plane quadrats can be defined by four numbers each of which is read on the axes of the grid, diagram 1.2.

The grid itself is a module of 1:

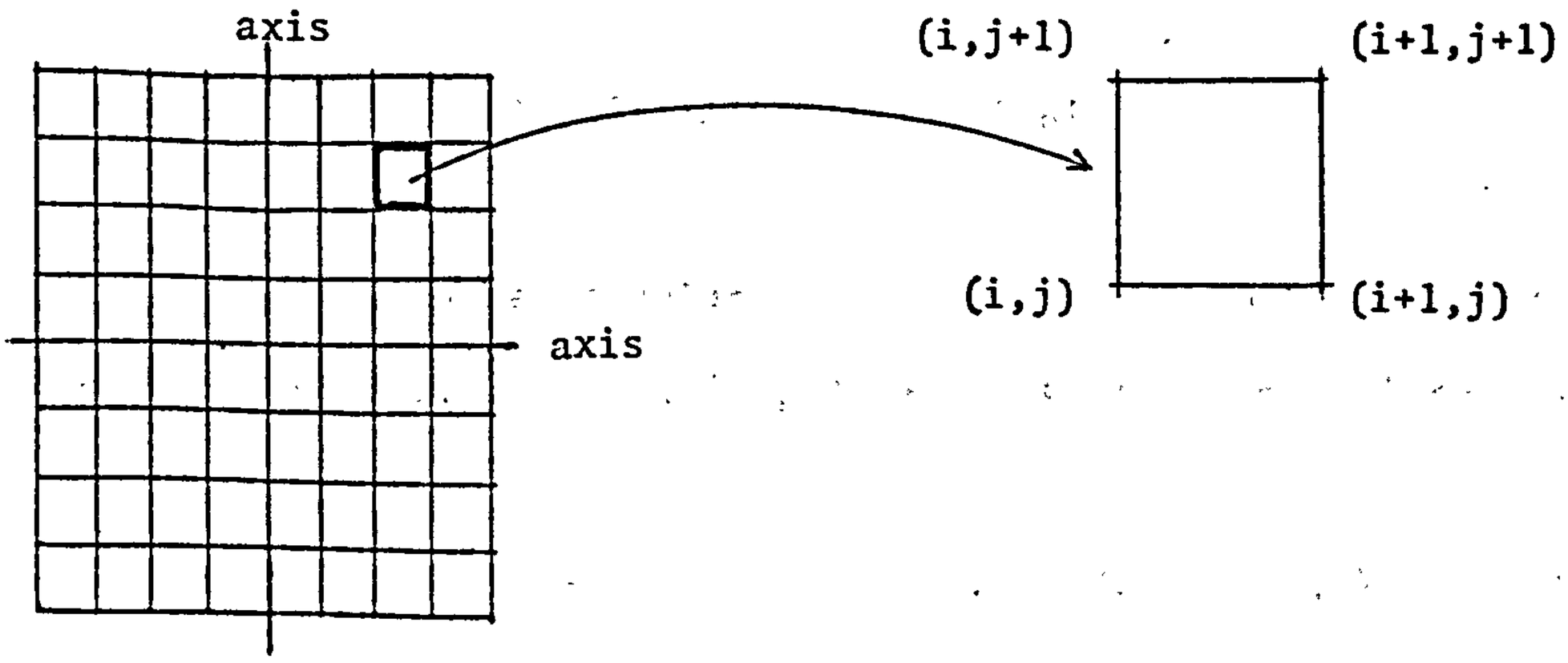
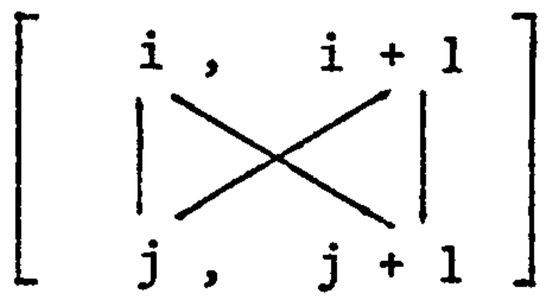


DIAGRAM 1.2

The quadrat can be fully defined by writing down the co-ordinates of its vertices as:

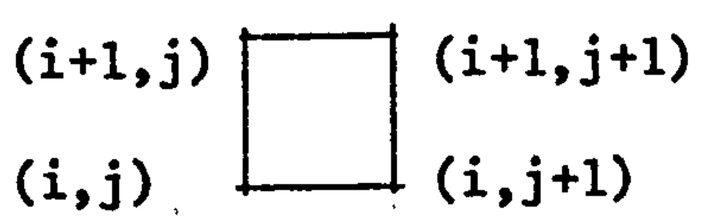


In this notation the vertical and diagonal combination of the reference numbers define the quadrat. A further shortened form is also suggested,

$$\langle i, j \rangle$$

thus

$$\begin{bmatrix} i, & i+1 \\ j, & j+1 \end{bmatrix} \equiv \langle i,j \rangle \equiv$$



9.10 A two dimensional shape composed of quadrats $\langle i,j \rangle$, $\langle i_1,j_1 \rangle$, $\langle i_2,j_2 \rangle$, ... $\langle i_n,j_n \rangle$ can be conceived as the union of the sets of points defined by these quadrats in two dimensional space.

It can be written as

$$\langle i:j \rangle \cup \langle i_1:j_1 \rangle \cup ..... \langle i_n:j_n \rangle$$

If it is a rectangular shape composed of successive quadrats for which i=1,2 ..... n and j=1, diagram 13, it can be written as

$$\bigcup_{i=1}^{i=n} \langle 1;j \rangle$$

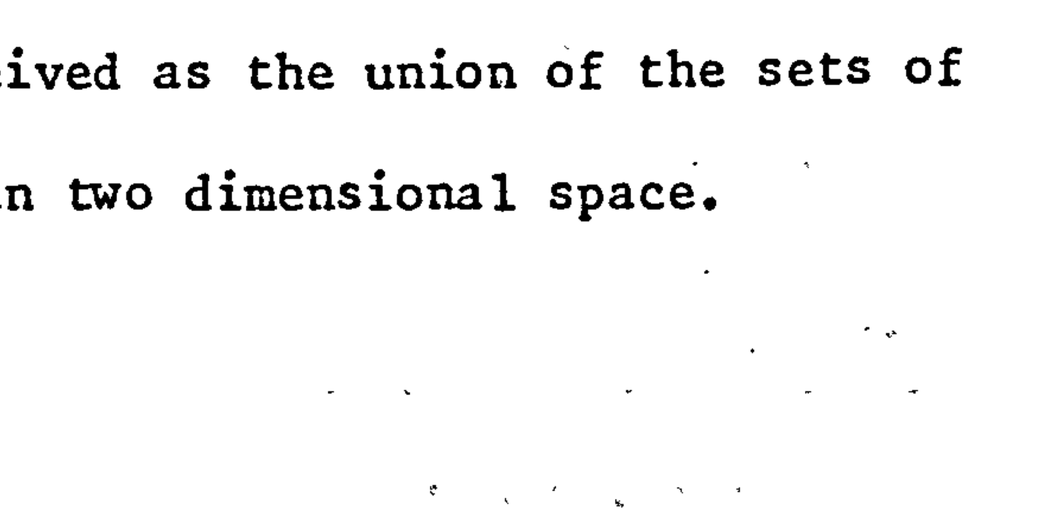


DIAGRAM 1.3

For a rectangular shape of successive quadrats where i=1 and

j=1, ..., m, diagram 14, the notation is

$$\bigcup_{j=1}^{j=m} \langle 1;j \rangle$$

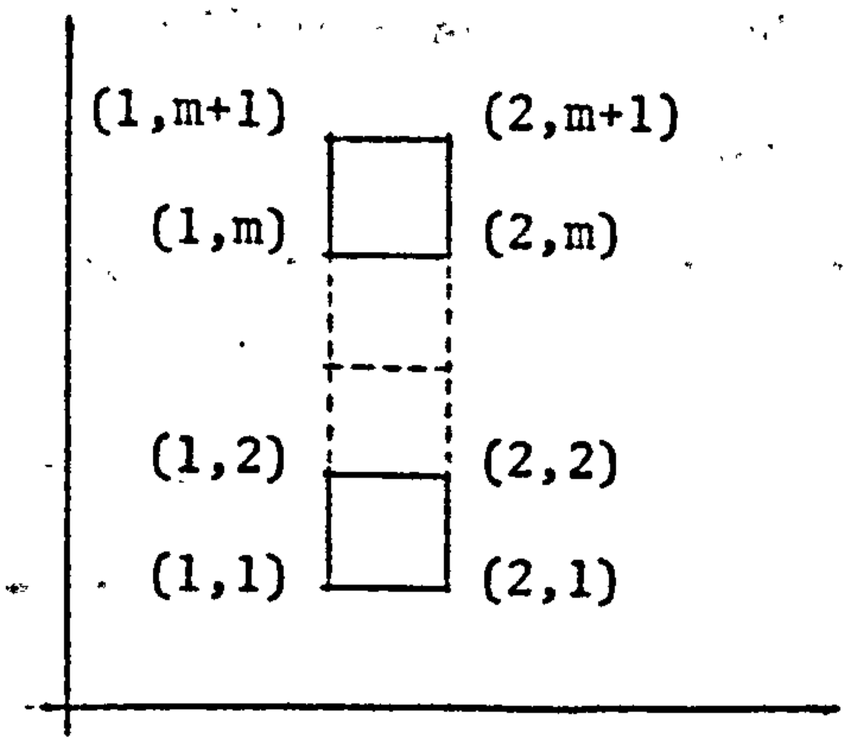


DIAGRAM 1.4

9.11 A rectangular shape of successive quadrats where i=1,2, ... n and j=1,2, ... m, diagram 1.5, is denoted by

$$\bigcup_{i=1}^{i=n} \bigcup_{j=1}^{j=m} \langle i;j \rangle$$

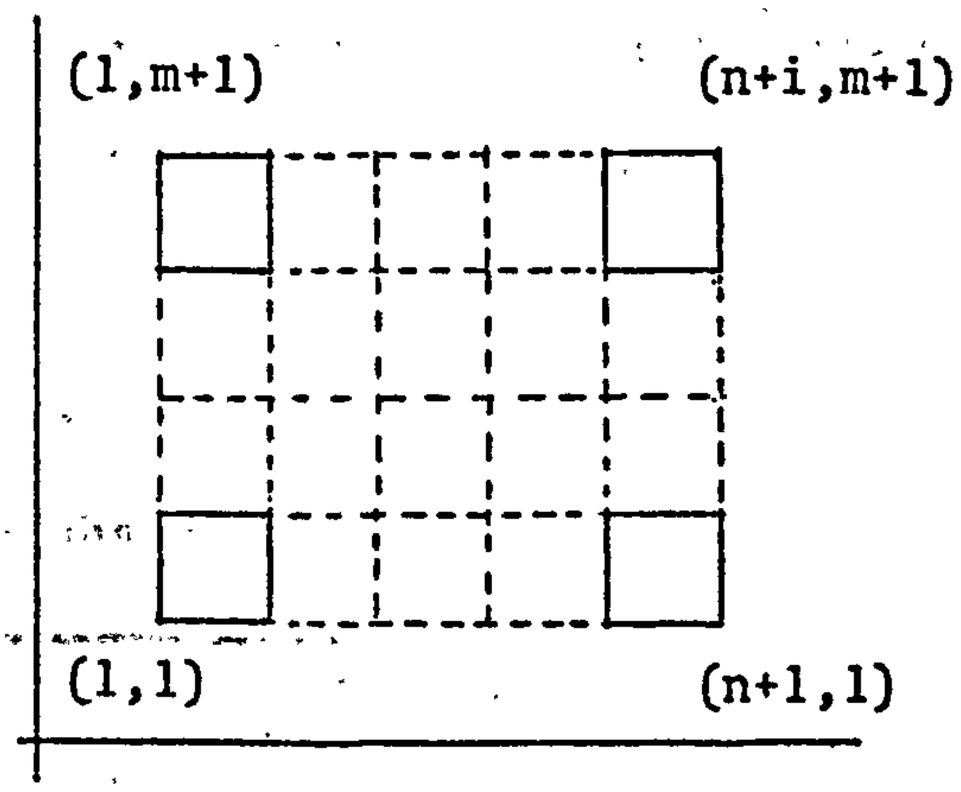


DIAGRAM 1.5

So continuous rectangular shapes can be defined on an appropriate grid and a reference system using the operations of union of sets or double union of sets as in the last case.

9.12 The operation of the intersection of sets can be employed to describe more complex shapes of composite rectangular forms. In this way we can define U-, L- and O- shaped plans in two dimensional space. The idea is to describe a larger rectangle which just encloses the shape to be described as well as the part to be carved away such that the remaining part of the large containing rectangle

is the desired shape. In set notation the containing rectangle, defined as a union of sets of quadrats, is indicated as set A and the part to be carved away as set a , diagram 1.6. Therefore the set L which is the desired shape is the intersection of the two sets A and $\acute{a}_1$:

$$L = A \cap a_1$$

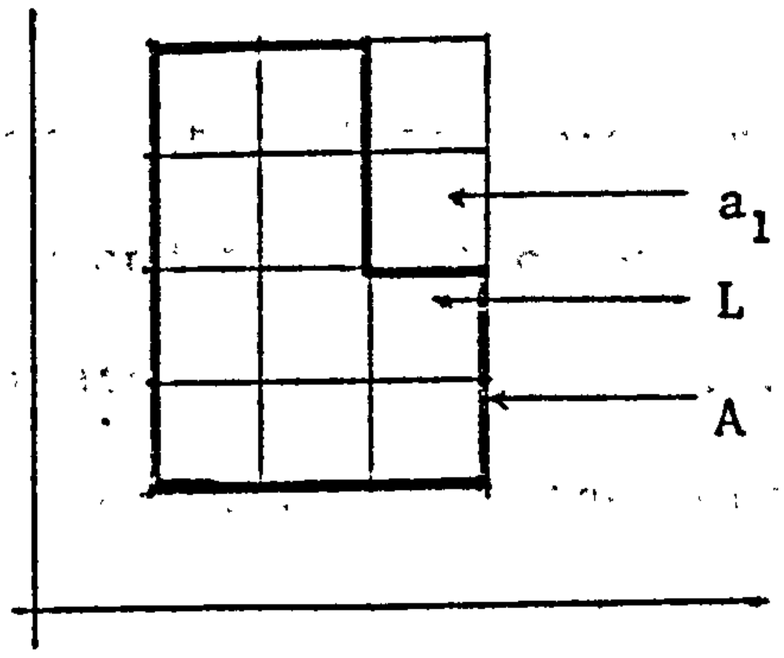


DIAGRAM 1.6

The same procedure applies to describing a U- and an O- shaped plan, diagrams 1.7and 1.8respectively. The notation becomes

$$U = A \cap \acute{a}_2 \quad \text{for the U- shaped plan}$$

and

$$O = A \cap \acute{a}_3 \quad \text{for the O- shaped plan}$$

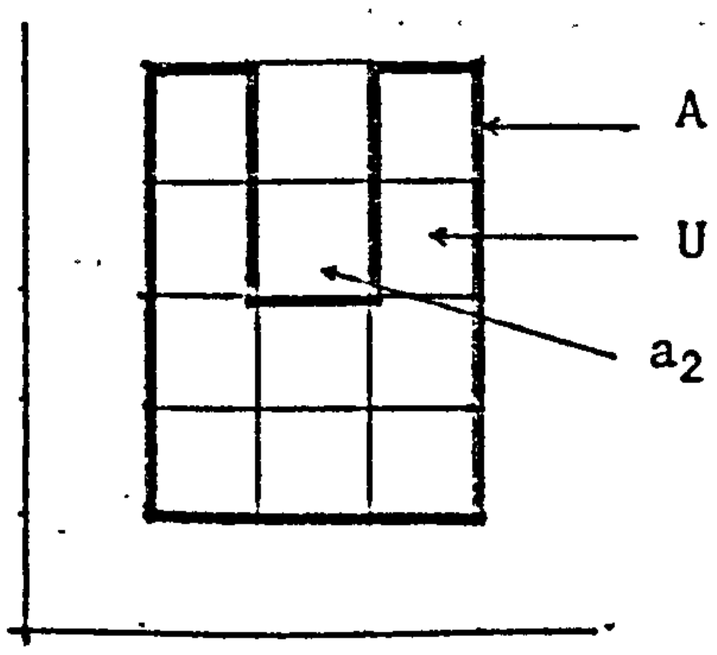


DIAGRAM 1.7

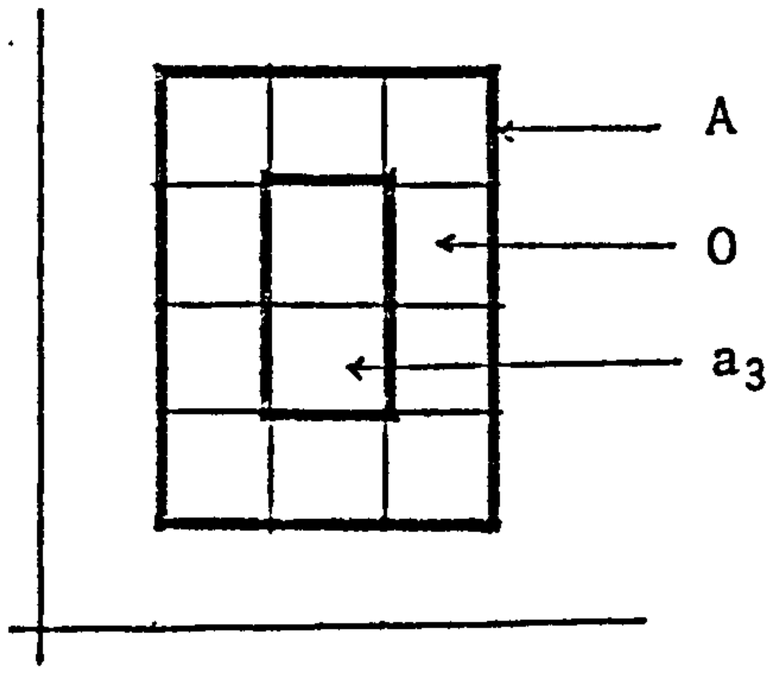


DIAGRAM 1.8

9.13 For three dimensional shapes, the form is thought of as a building up of unit cubes - cubelets. With reference to a three dimensional grid and axes the corners of unit cubelets can be defined. As in the two dimensional case solids can be regarded as the unions of the cubelets which form them. The coordinates defining the position of a cubelet can be written as

$$\begin{bmatrix} i, & i+1 \\ j, & j+1 \\ k, & k+1 \end{bmatrix}$$

where i,j and k are the coordinates of one corner referred to the x, y and z axes respectively and the eight corners of the cubelet can be specified by appropriate combinations of i,j,k, i+1, j+1 and k+1. The notation can be shortened to the format

<i;j;k>

For a block where i=1,2, ...n, j=1 and k=1 the description of the block, which is the union of the specified cubelets is written as

<1;1;1>∪<2;1;1>∪ .... ∪<n;1;1>

or shortly

$$\bigcup_{i=1}^{i=n} \langle i;1;1\rangle$$

The same procedure applies where i=1, j=1, 2, ...m and k=1

$$\bigcup_{j=1}^{j=m} \langle 1;j;1\rangle$$

or where i=1, j=1 and k=1,2, ...p,

$$\bigcup_{k=1}^{k=p} \langle 1;1;k \rangle$$

In general a rectangular block can be described by the union of the cubelets forming it and can be given the symbolism

$$\bigcup_{k=1}^{k=p} \bigcup_{j=1}^{j=m} \bigcup_{i=1}^{i=n} \langle i;j;k \rangle$$

9.14 Rectangular three dimensional shapes with rectangular holes or protrusions can also be described by applying the operation of set intersection as in the case of two dimensional shapes. The only difference is the extra third dimensional reference.

9.15 Set theoretic based descriptors can also be developed to define spatial relationships between objects . This, however, is again restricted to rectangular shapes with an appropriate module. There are two types of spatial relations between any two given objects: overlap or conjunction (the case where the two objects do not join is regarded as one of non-overlap). The overlap relationship is of four types: non-overlap (distinctive), partial, inclusive and identical. Conjunction can be in the form of stacking, nesting or fitting. The meaning of these types of relationships between objects is shown in tables 1, 2. Here two rectangular shapes are described as sets of points A and B. In table 1 the overlap conditions are shown graphically and interpreted in set notation. In table 2 in addition to the specification of A and B as sets of points the terminal points of the objects are also specified as a_1, a_2 for A and b_1, b_2 for B. By such specification the number of ways in which conjunction occurs is more closely defined.

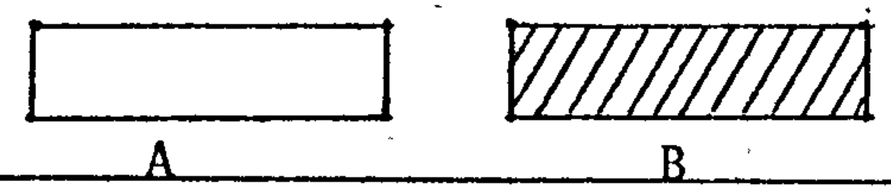
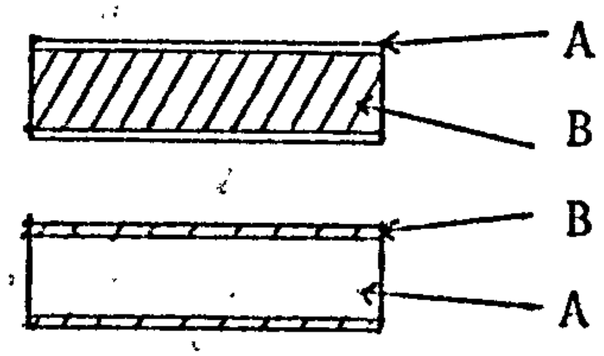
CONDITION	TYPE OF OVERLAP	GRAPH
1. if $A \cap B=0$	none, disjunctive	
if $A \cap B \neq 0$, then:		
2. $A \not\subset B$, $B \not\subset A$	partial	
3. $A \not\subset B$, $B \subset A$	inclusive	
4. $A \subset B$, $B \not\subset A$		
5. $A \subset B$, $B \subset A$	identical	

TABLE 1.1

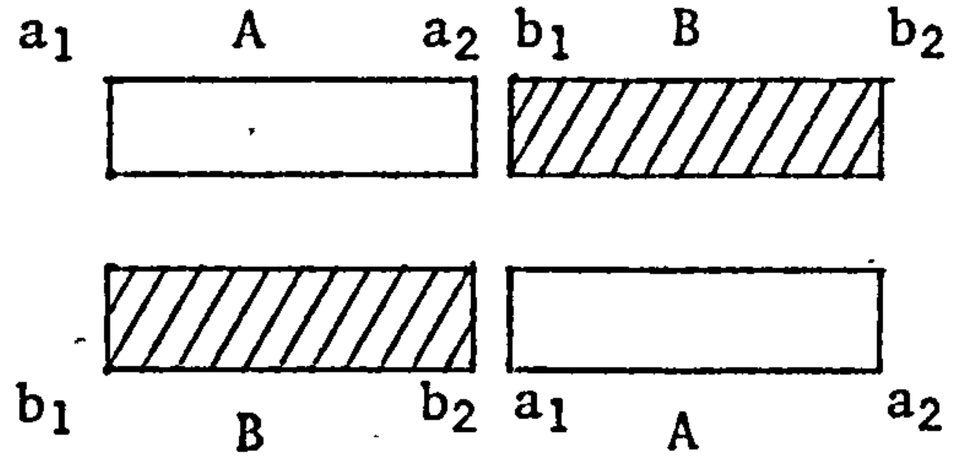
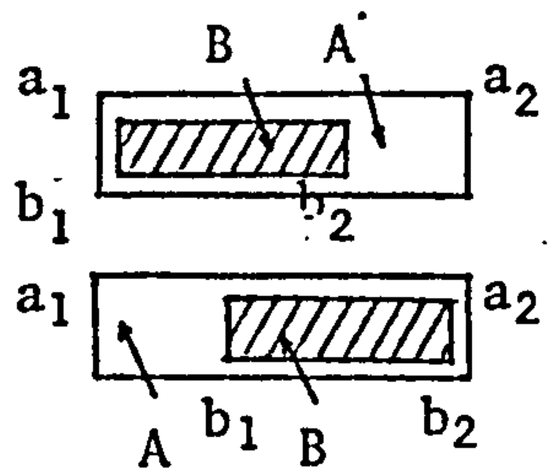
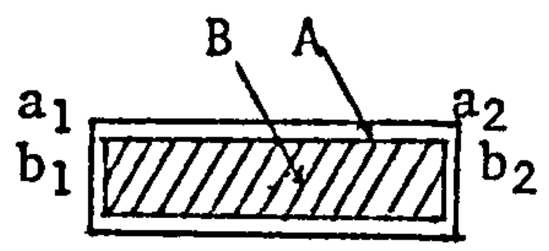
CONDITION	TYPE OF CONJUNCTION	GRAPH
$A \not\subset B$, $B \not\subset A$ 1. $a_2 = b_1$ 2. $a_1 = b_2$	stacking	
$A \not\subset B$, $B \subset A$ ($A \subset B$, $B \not\subset A$) 3, 5 $a_1 = b_1$ 4, 6 $a_2 = b_2$	nesting	
7. $A \subset B$, $B \subset A$ $a_1 = b_1$ $a_2 = b_2$	fitting	

TABLE 1.2

10.00 CONCEPTS FROM GROUP THEORY

10.01 Using group theory a method of form description can be formalized to deal with structures and arrangements that show symmetry of form. A group is a set, G, of elements a,b,c, ... for which there exists a rule of combination such that;[44]

a) any two elements can be combined to form a product which is an element of the set:

$$\text{for every } a,\ b \varepsilon G \text{ then } ab \varepsilon G \quad (ab \neq ba)$$

b) for every $a,b,\ c \varepsilon G$

$$(ab)c = a(bc)$$

which is known as the associative law of group products.

c) the set G contains a unit (null or neutral) element e such that for all $a \varepsilon G$

$$ae = ea = a$$

d) for every $a \varepsilon G$ there exists an element a^{-1} of G called the inverse of a such that

$$aa^{-1} = a^{-1}a = e$$

10.02 A group is called abelian (or commutative) if for every pair of elements $a,\ b \varepsilon G$, then

$$ab = ba$$

10.03 Any finite set of elements satisfying the four group axioms is said to form a finite group. The order of a group is the number of elements in the set. If the group does not have a finite number of elements it is called an infinite group.

A group in which all the elements can be expressed as powers

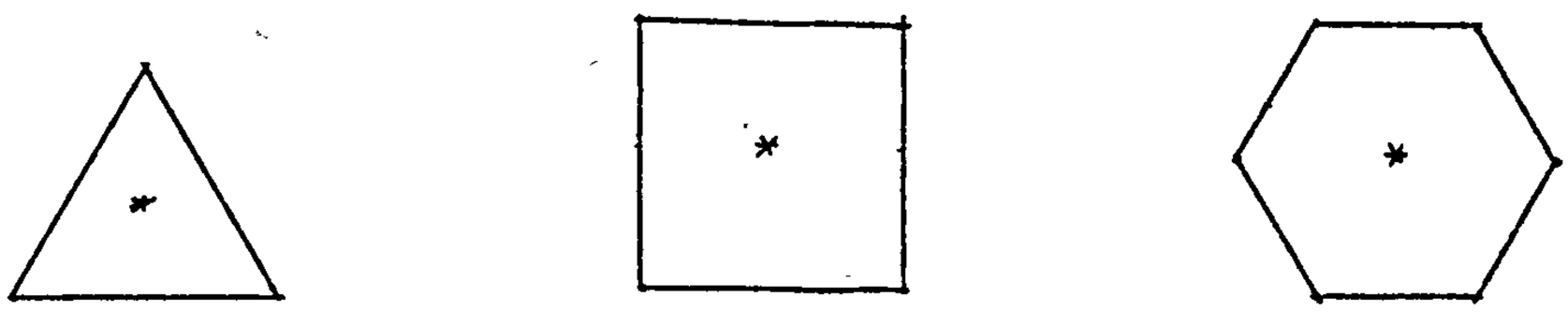
of a single element is called a cyclic group.

Two groups are isomorphic if there exists a one-to-one correspondence between their elements.

11.00 SYMMETRY

11.01 Symmetry of form is shown by many natural and man-made structures: in plants, crystals, or buildings of certain architectural styles. It is a special case of composition of elements or objects in a high degree of spatial order about one or more axes and/or planes. Operators can be applied to generate complex symmetries from simple ones. Group Theoretic concepts help to reconstruct the generative formulae of given symmetries, and has, therefore, found wide application in crystallography.[44]

11.02 The simplest type of symmetry is that about an axis and is called axial symmetry. The vertices of an equilateral triangle, a square and a hexagon with their centres of mass carrying an axis normal to the plane of the paper form a three fold, four fold and six fold symmetry axes respectively, diagram 1.9 a,b,c.



a b c

DIAGRAM 1.9

11.03 The essential feature about an axial symmetry is that rotating the elements (in this example the vertices) through an angle $2\pi/n$ produces geometrical coincidence for the elements (n being the number

of elements). Rotation through 2π restores the original location of the elements.

In addition to symmetry axes regular polygons have also symmetry planes passing through the axes. These are shown by the dotted lines in diagram 1.10.

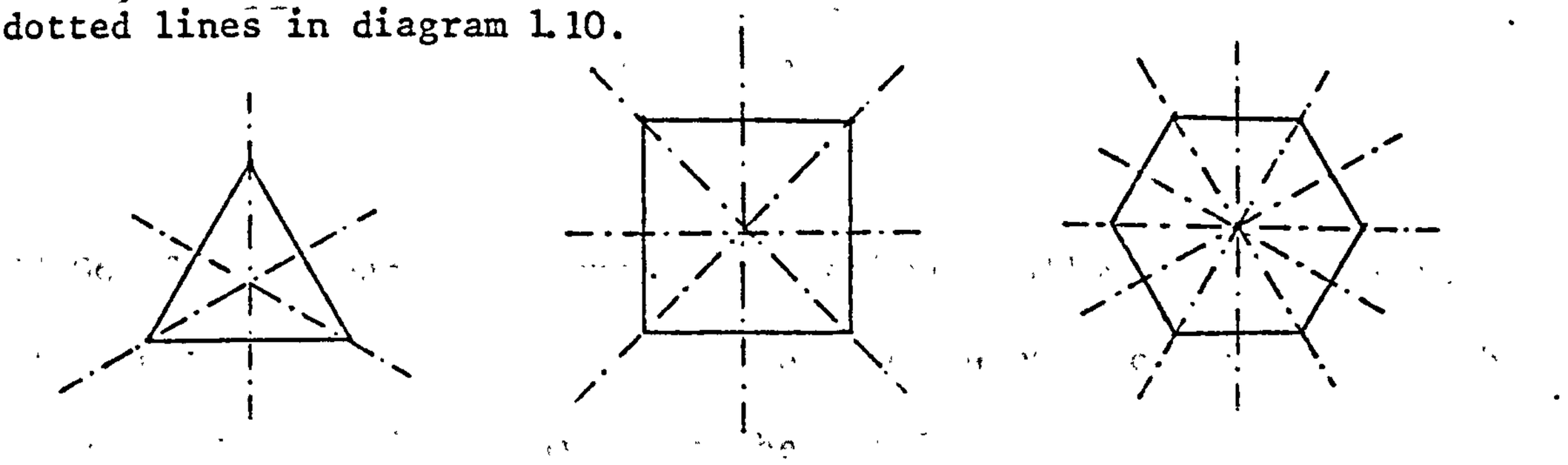


DIAGRAM 1.10

11.04 Reflecting through the symmetry plane of a regular polygon produces geometrical self coincidence. Normal to these planes regular polygons can produce geometrical self coincidence by reflecting onto a plane parallel to their own. A further type of symmetry of the regular polygon is about horizontal axes parallel to their own plane. These are shown in diagram 1.11.

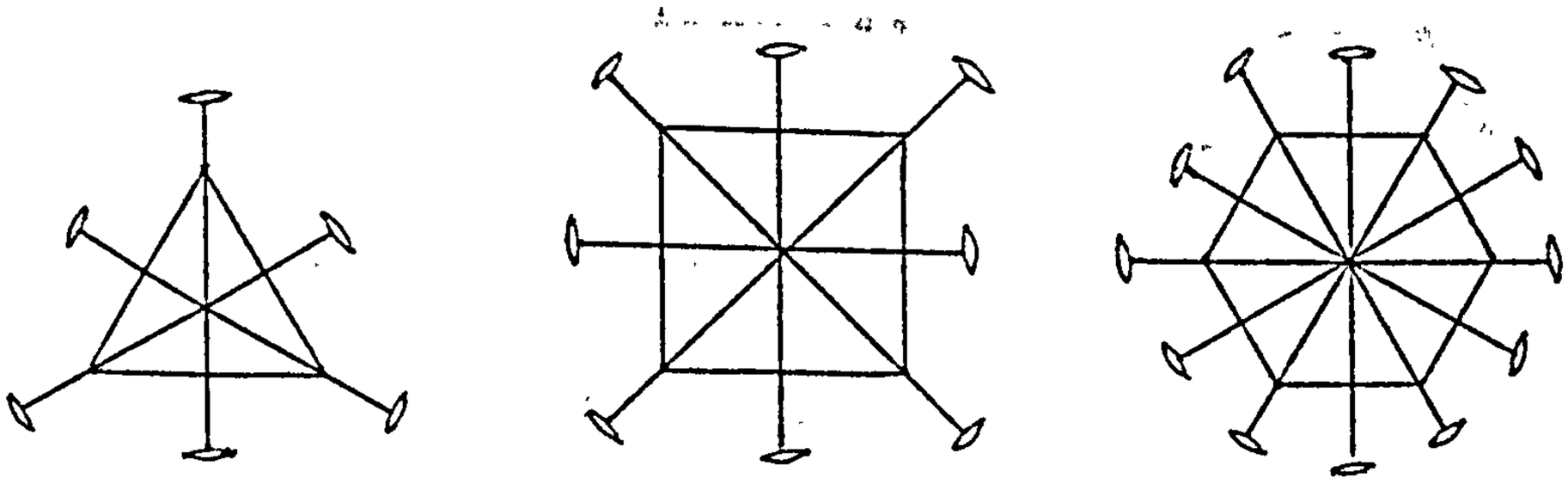


DIAGRAM 1.11

11.05 A further type of symmetry can be achieved by inversion through a centre. This type is shown by the parallelogram, square and hexagonal arrangements shown in diagram 1.12. The arrows connect elements which are inverses with respect to the centre.

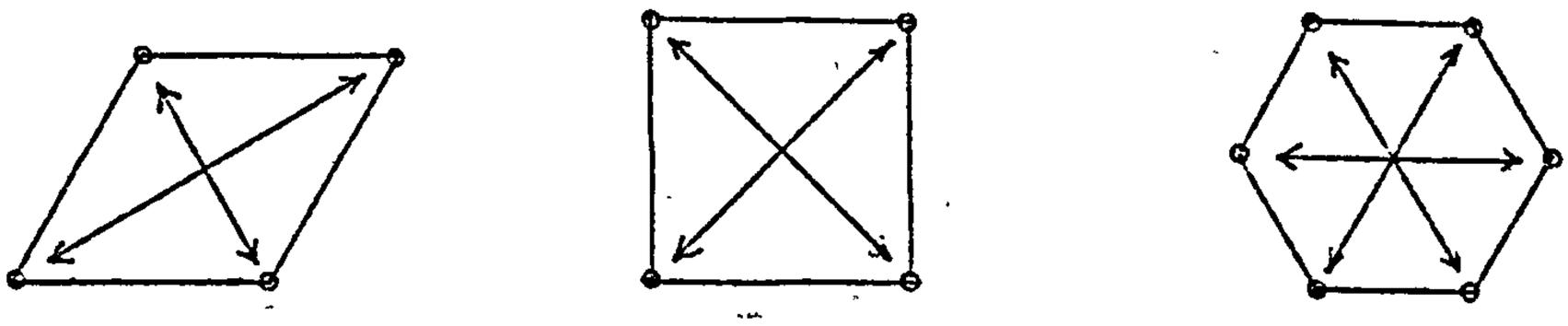


DIAGRAM 1.12

11.06 The presence of a symmetric motif unit allows symmetries to arise with the horizontal 2-fold axes and the vertical mirrors. This type of symmetry disappears when the motif unit is asymmetric. An example of this is to have two units instead of one unit motif about the vertices of the triangle, square and hexagon. This is shown by diagram 1.13

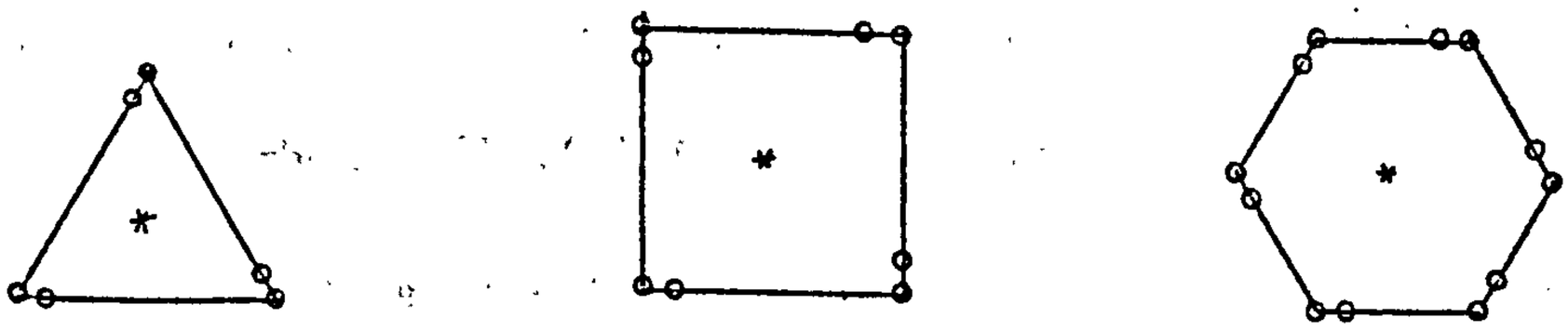


DIAGRAM 1.13

12.00 THE DEVELOPMENT OF A NOTATION

12.01 To describe symmetry there should be a way of denoting the symmetry elements: the motif, the motif structure and the relevant axes and/or planes. These aspects are considered with respect to diagram 1.14.

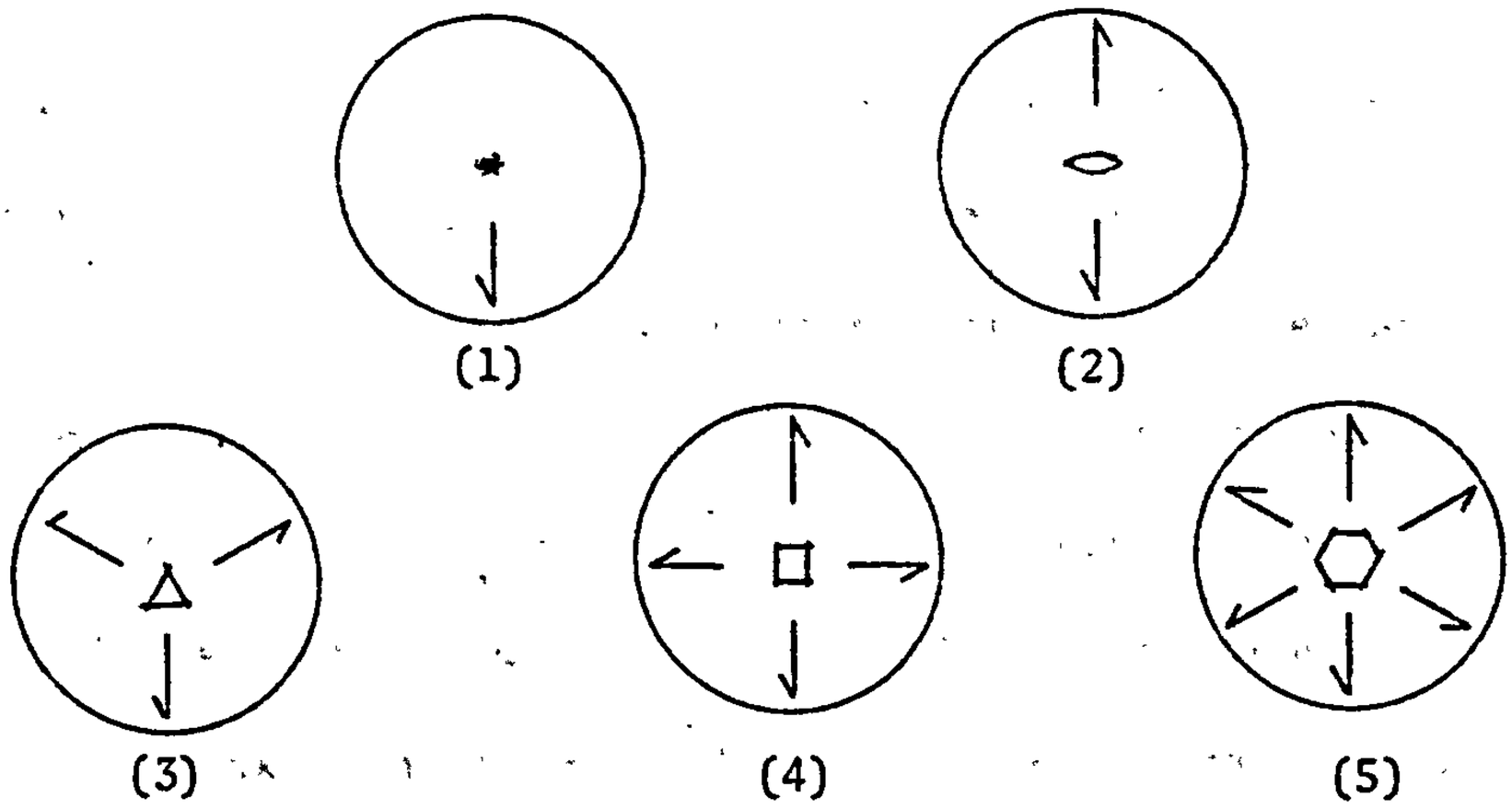


DIAGRAM 1.14: GENERATION OF A MOTIF STRUCTURE FROM A MOTIF UNIT BY A VERTICAL SYMMETRY AXIS.

In the diagram the relevant axes are denoted by a geometrical symbol (1-fold, 2-fold, 3-fold, 4-fold, and 6-fold symmetry axes). The axis is imagined to be normal to the plane of the paper and the plane of the motif is imagined to be parallel to another symmetry plane which can be introduced later. The motif elements are asymmetrical in shape and their generation by the relevant symmetry axis is referred to as the motif structure. The circle emphasizes its rotational significance. The motif structure is denoted by a mathematical symbol: (1),(2),(3),(4) and (6).

12.02 The next development in the notation is to combine the previous symmetry axes with other symmetry elements: vertical mirrors; diagram 1.15;axes automatically generated by introducing the vertical mirror symmetries, diagram1.16; horizontal mirrors, diagram 1.17; combinations of an n-fold vertical axis and a horizontal 2-fold axis (dihedral symmetries), diagram 1.18. Further the introduction of a 2-fold horizontal axis automatically generates others, diagram 1.19. Combining dihedral symmetries with a horizontal mirror produces a further set of symmetries, diagram 1.20.

12.03 All these types of symmetry have been assigned appropriate descriptors (diagrams 1.15-1.20.Thus if the symmetry is due to an axis then a number denoting the motif structure is given and is usually equal to the number of motif units. For a hexagon the symmetry units due to a vertical axis is six and is denoted by 6. When an axis is combined with a horizontal mirror the notation becomes $\frac{6}{m}$. An axis and a 2-fold horizontal axis symmetry is denoted by 22 after the number indicating the motif structure due to the axis only. The first 2 in 22 indicates the original symmetry due to the 2-fold horizontal axis and the second 2 designates the symmetry due to the axis automatically generated. The 6-fold axis combined with a 2-fold horizontal axis symmetry is, thus, 622.

12.04 The combination of an axis and a vertical mirror is denoted by an mm after the number designating the symmetry due to the vertical axis. Thus a 6-fold axis combined with a vertical mirror produces the symmetry 6mm. Here, the first m denotes the symmetry due to the original mirror and the second is the symmetry due to the vertical mirrors automatically introduced as a result of the first mirror.

12.05 A symmetry produced by the combined effect of a vertical axis, a vertical mirror and a horizontal mirror is the same as that resulting from the combination of an axis with a 2-fold horizontal axis and a horizontal mirror. Accordingly the notation is a combination of the notation of the latter: a 6-fold axis combined with a vertical mirror and a horizontal mirror produces the symmetry $\frac{6}{m}\frac{2}{m}\frac{2}{m}$.

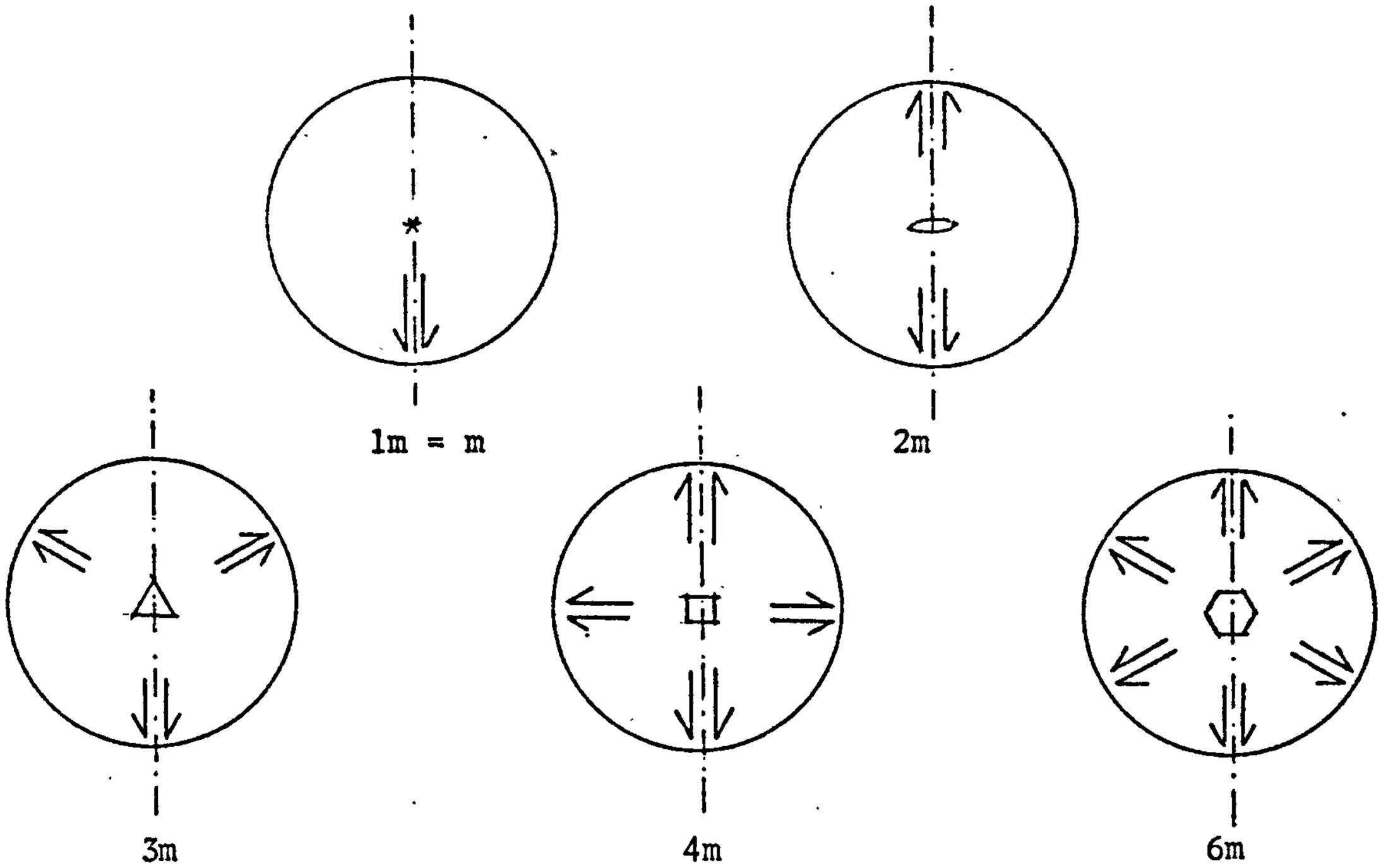


DIAGRAM 1.15: GENERATION OF MOTIF STRUCTURY BY A VERTICAL SYMMETRY AXIS COMBINED WITH A VERTICAL MIRROR.

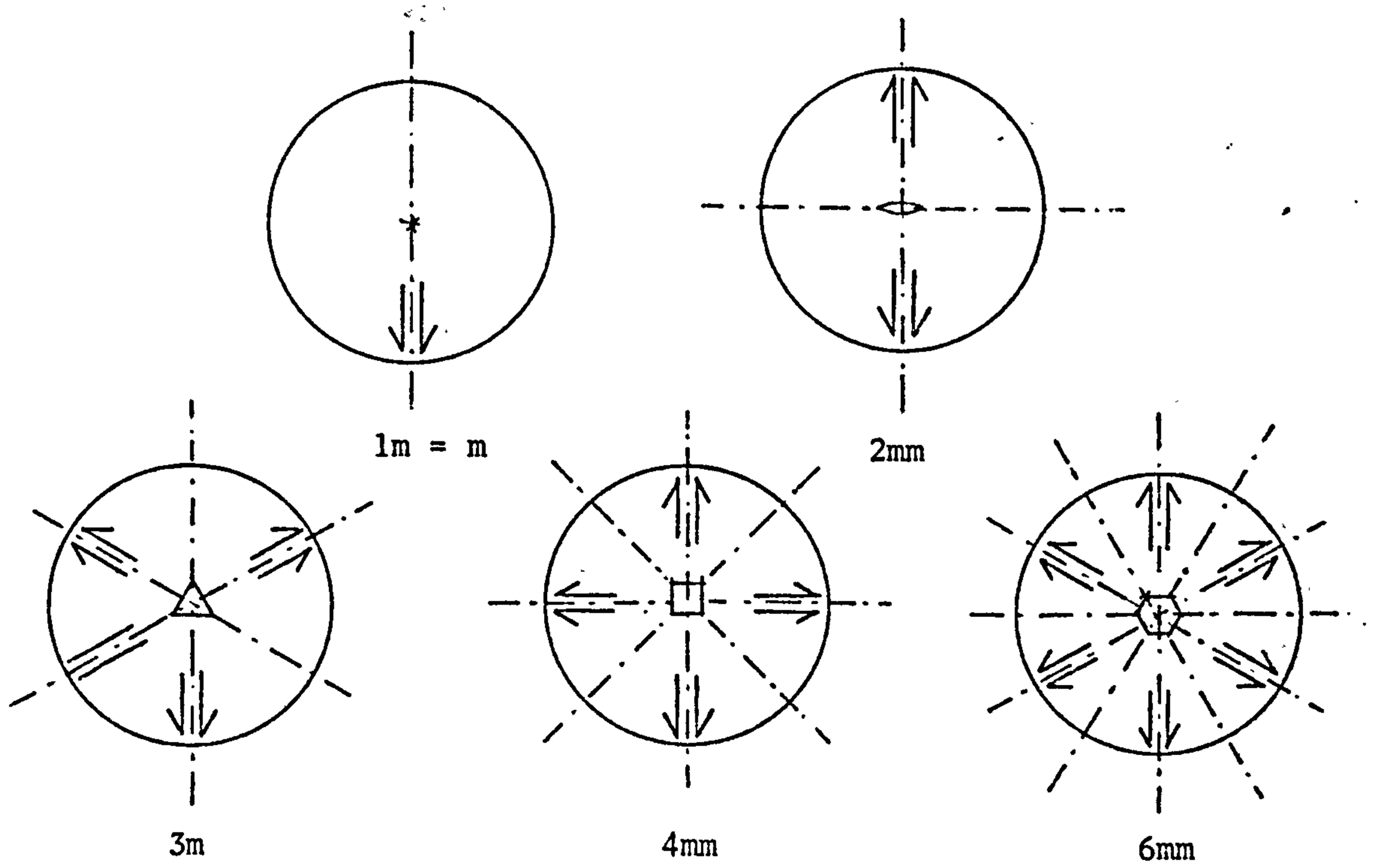
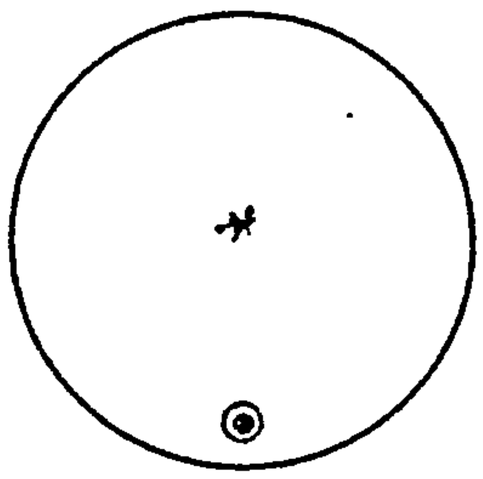
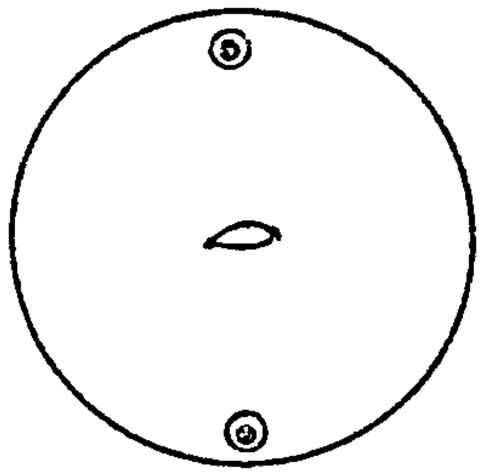


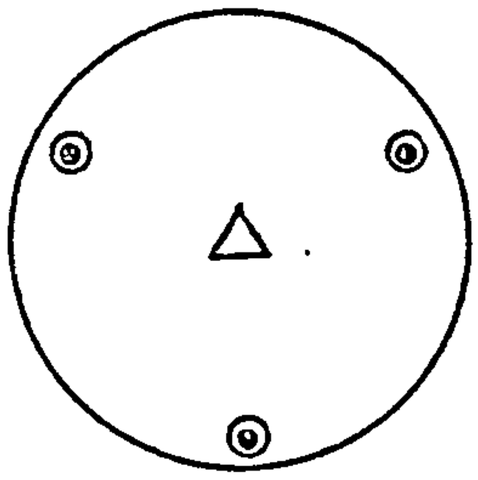
DIAGRAM 1.16: THE SAME CONFIGURATION AS 1.15, BUT EXHIBITING THE EXTRA VERTICAL MIRRORS AUTOMATICALLY INTRODUCED.



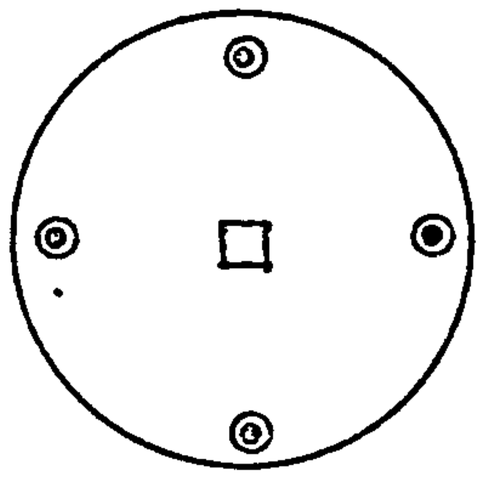
1
m



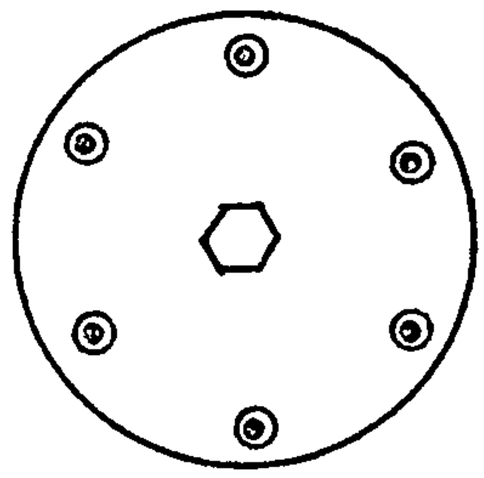
2
m



3
m

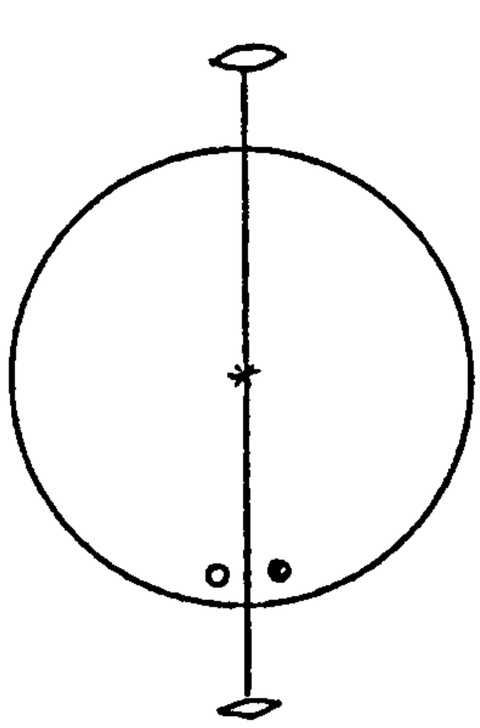


4
m

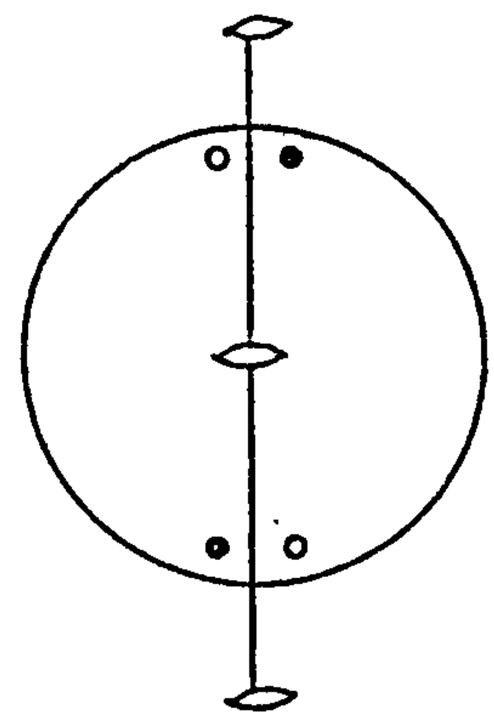


6
m

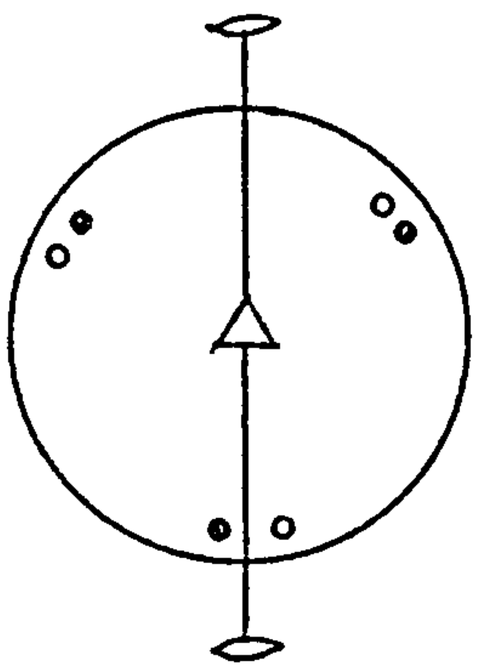
DIAGRAM 1.17: FOR SIMPLICITY, THE MOTIF UNIT IS REPLACED BY ○ , ITS HORIZONTAL MIRROR IMAGE BEING INDICATED BY ◒ . THE MOTIF AND ITS IMAGE LIE IN TWO PARALLEL, BUT SEPARATE, PLANES.



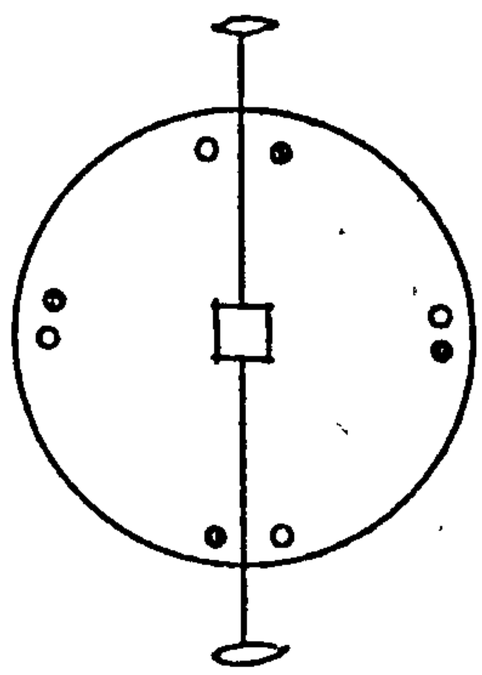
12 = 2



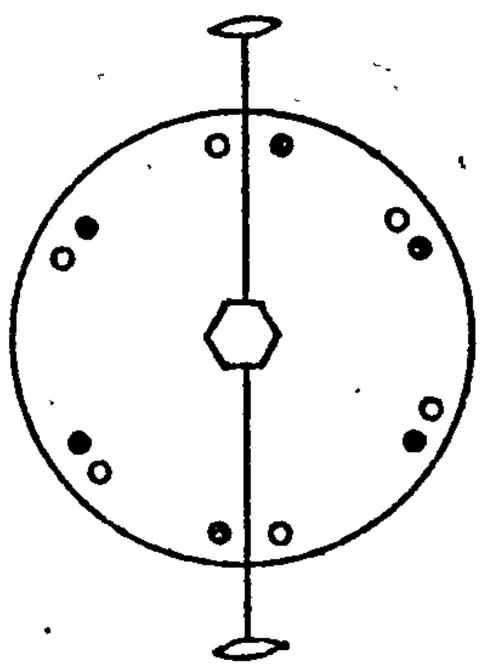
22



32

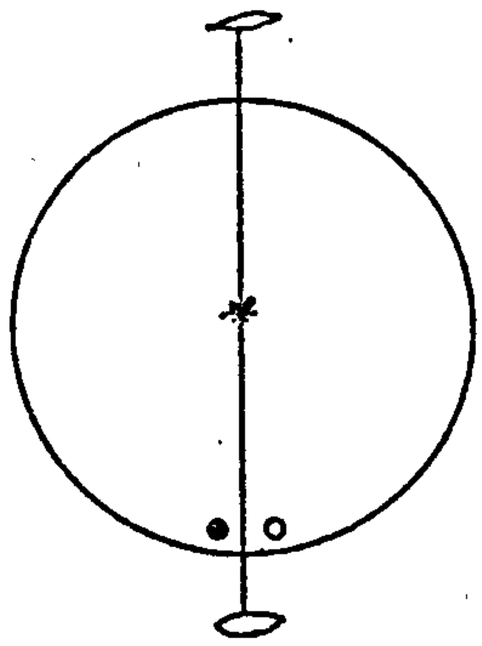


42

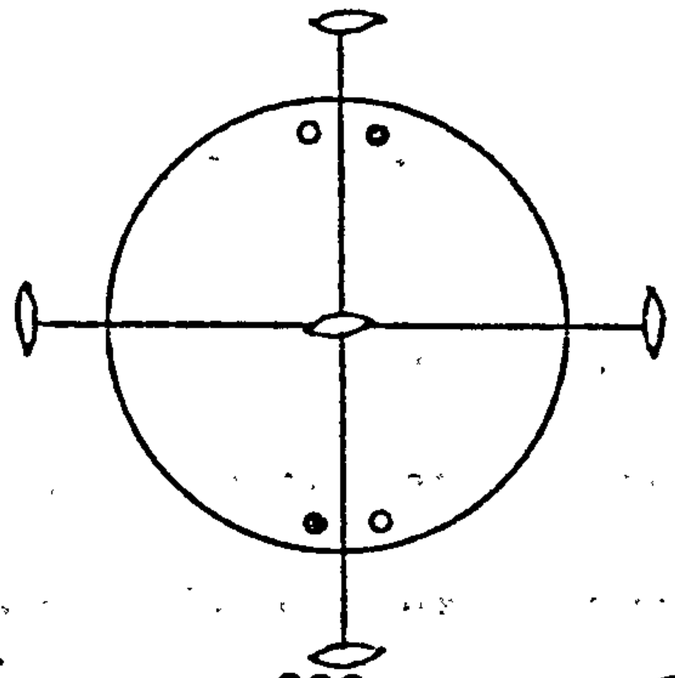


62

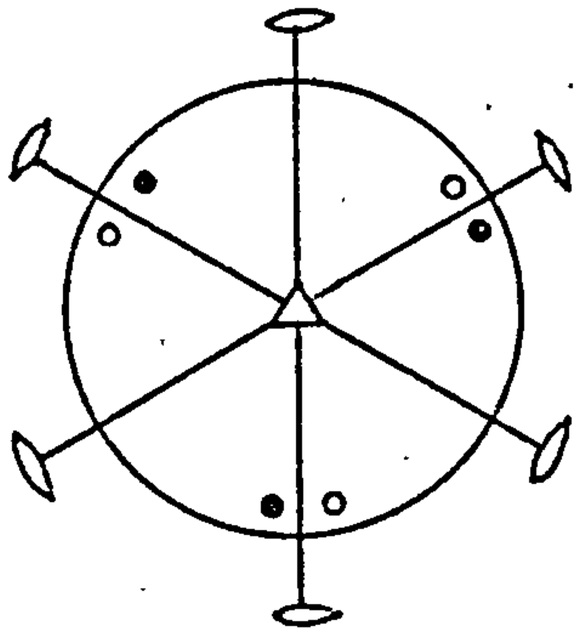
DIAGRAM 1.18: COMBINATION OF VERTICAL SYMMETRY AXIS WITH A HORIZONTAL 2-FOLD AXIS AND ARE LYING IN TWO DIFFERENT, BUT PARALLEL, PLANES.



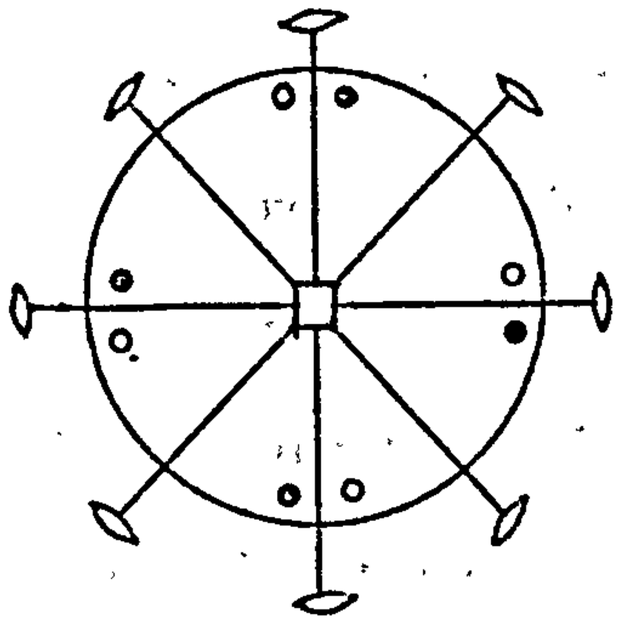
12 = 2



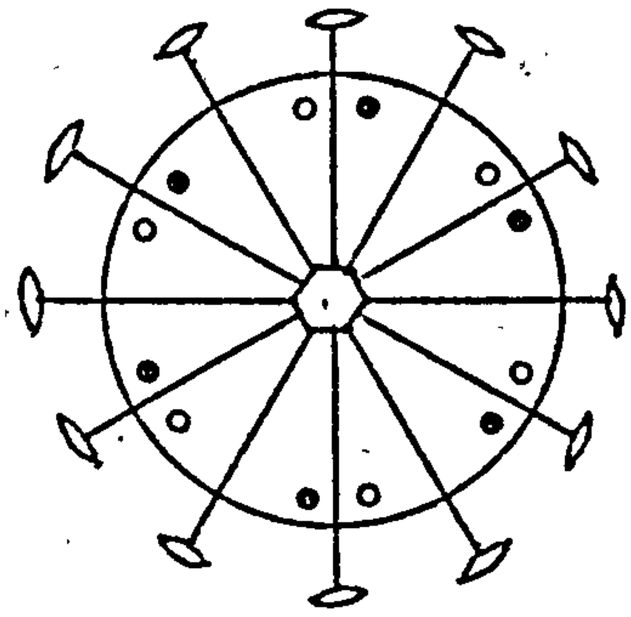
222



32

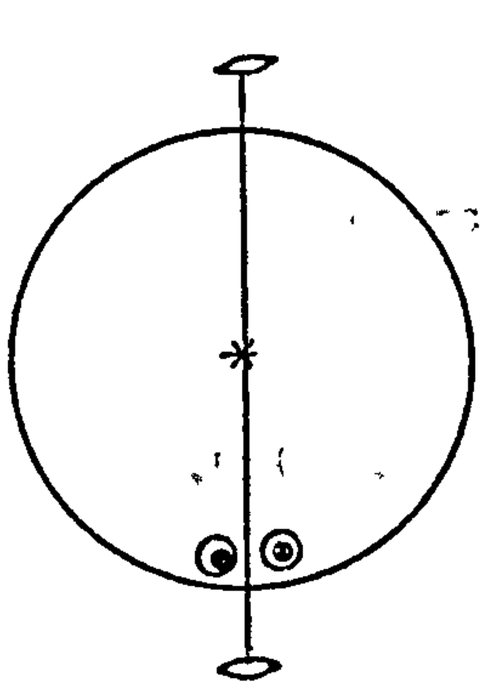


422

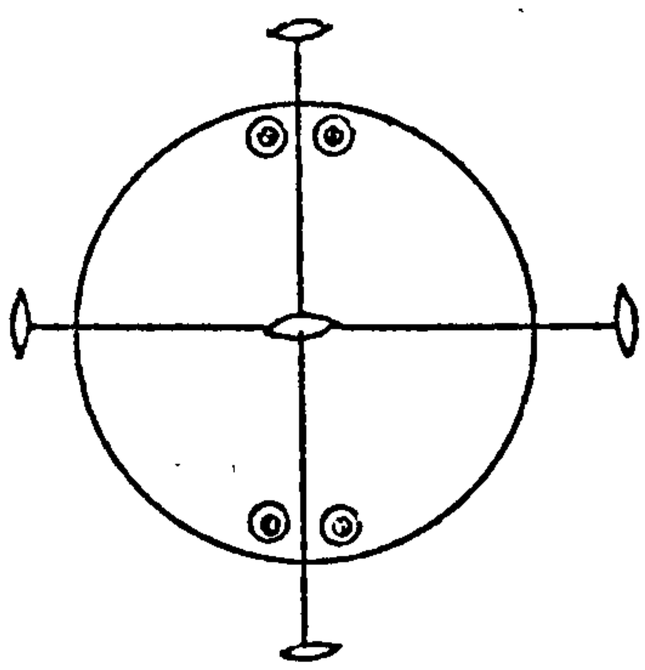


622

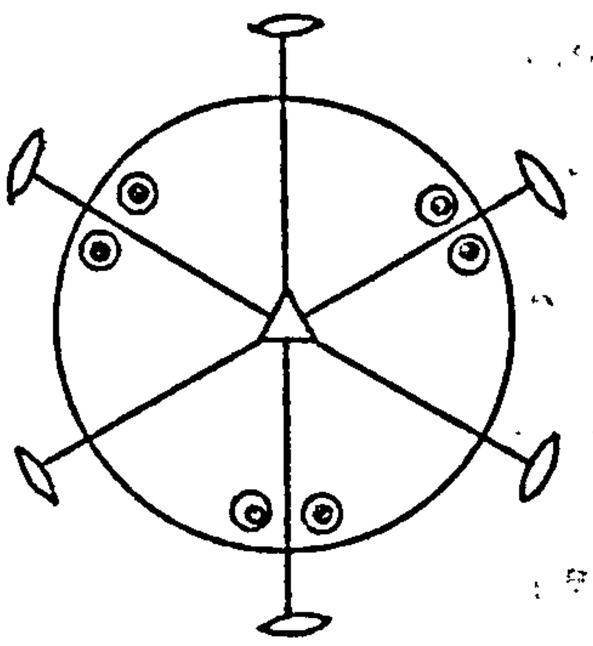
DIAGRAM 1.19: THESE ARE THE SAME CONFIGURATIONS AS IN DIAGRAM 1.18, BUT EXHIBITING THE EXTRA HORIZONTAL 2-FOLD AXES AUTOMATICALLY INTRODUCED.



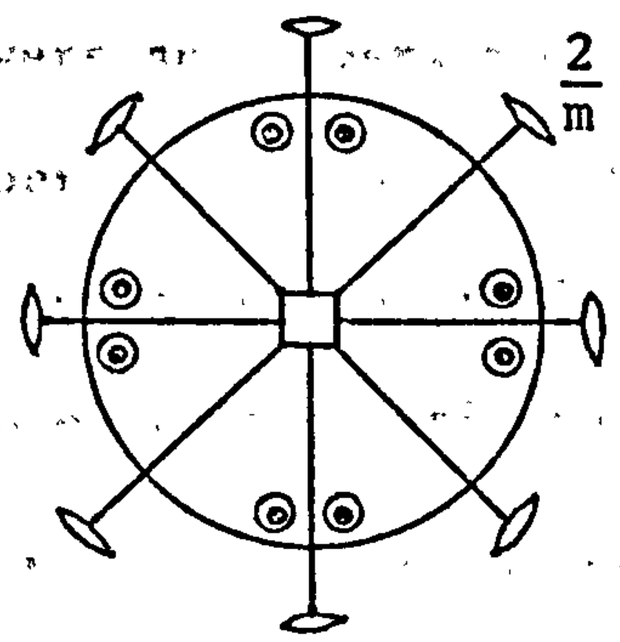
2mm



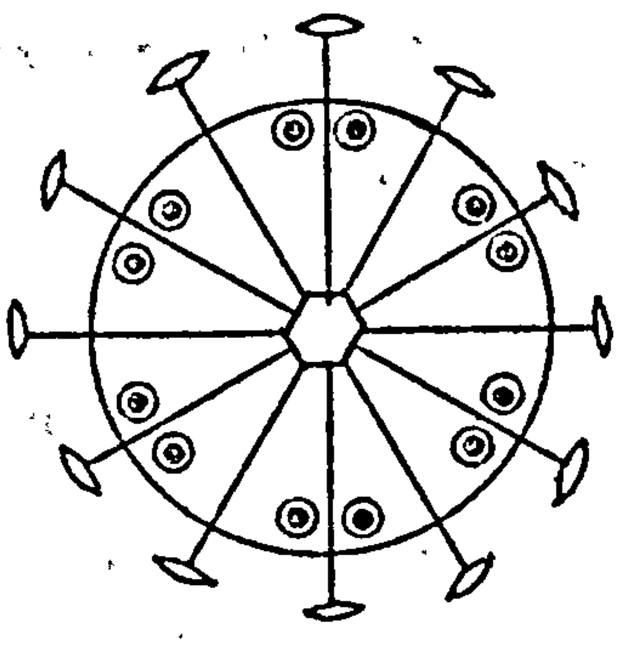
$\frac{2}{m}\frac{2}{m}\frac{2}{m}$



$\frac{3}{m}$m2



$\frac{4}{m}\frac{2}{m}\frac{2}{m}$



$\frac{6}{m}\frac{2}{m}\frac{2}{m}$

DIAGRAM 1.20: COMBINATION OF A HORIZONTAL MIRROR WITH THE CONFIGURATIONS EITHER OF DIAGRAM 1.19 OR DIAGRAM 1.16.

13.00 THE GROUP THEORETIC PROPERTIES OF SYMMETRY

13.01 Much of the axial symmetry can be described by a rotation operation around an axis. Denoting by C an operator which produces a rotation of $\frac{2\pi}{n}$ around an axis (n being the number of symmetry units), then C^2 describes an axial rotation through $4\pi/n$. In general C^r describes an axial rotation through $2\pi r/n$ and C^n restores the arrangement to its original structure. It is therefore equivalent to an identity matrix I which leaves the original composition unchanged. C^{-1} describes a rotation through $2\pi/n$ but in the opposite direction to that of C and is therefore equivalent to C^{n-1}. In general,

$$C^{-r} = C^{n-r}$$

Since in the set of operators

$$I, C, C^2 \ldots\ldots, C^{n-1};\quad C^n = I$$

I is included, powers and inverses of operators belong to the set and products of operators belong to the set it must therefore constitute a group. According to the previous definition of a cyclic group this set of operators constitutes a cyclic group.

13.02 Another operator, M, can be defined to describe the reflections through a symmetry plane. This operator has the properties

$$M^2 = I$$

and

$$M^{-1} = M$$

which imply that applying it twice restores the identity of the element and that it is similar to its inverse.

13.03 The operator M can be combined with C to generate a set of operators which define combinations of rotation and reflection, CM, or reflection and rotation MC. The combinations of the two operators forms a group and when it applies to symmetries based on 1,2,3,4 and 6 elements they form a cyclic group.

13.04 A further type of operator is the reflection operator D which satisfies the identity and inverse conditions of M but operates on a vertical plane passing through the axis. When D operates together with C a number of n-1 composite operators, CD, C^2D, ..., C^nD are evolved. These operators describe reflections through the other vertical planes automatically generated. The combination of C and D introduces a set of 2n operators:

$$I \quad C \quad C^2 \ldots\ldots C^{n-1}$$

$$C^n = D^2 = (CD)^2 = I$$

$$D \quad CD \quad C^2D \ldots\ldots C^{n-1}D$$

which forms a non-abelian group known as a dihedral group.

13.05 The above presentation illustrates the application of group theoretic concepts in identifying the order which a system of symmetrical elements or a structure in space possesses. Our conception of symmetry is a matter of visual and intuitive realization of order in the arrangements concerned but group theoretic descriptions, through sets of operators, externalize this realization by reconstructing it through systematic mathematical symbolism and manipulation.

The application of symmetry in the design of built form is discussed by March and Steadman with extensive illustrations of individual buildings, groups of buildings and urban layouts.

Symmetry, however, is shown in more complex three dimensional structures in crystallography. Through appropriate sets of operators and vectors very complex patterns of such arrangements can be shown to possess mathematically discernible order.

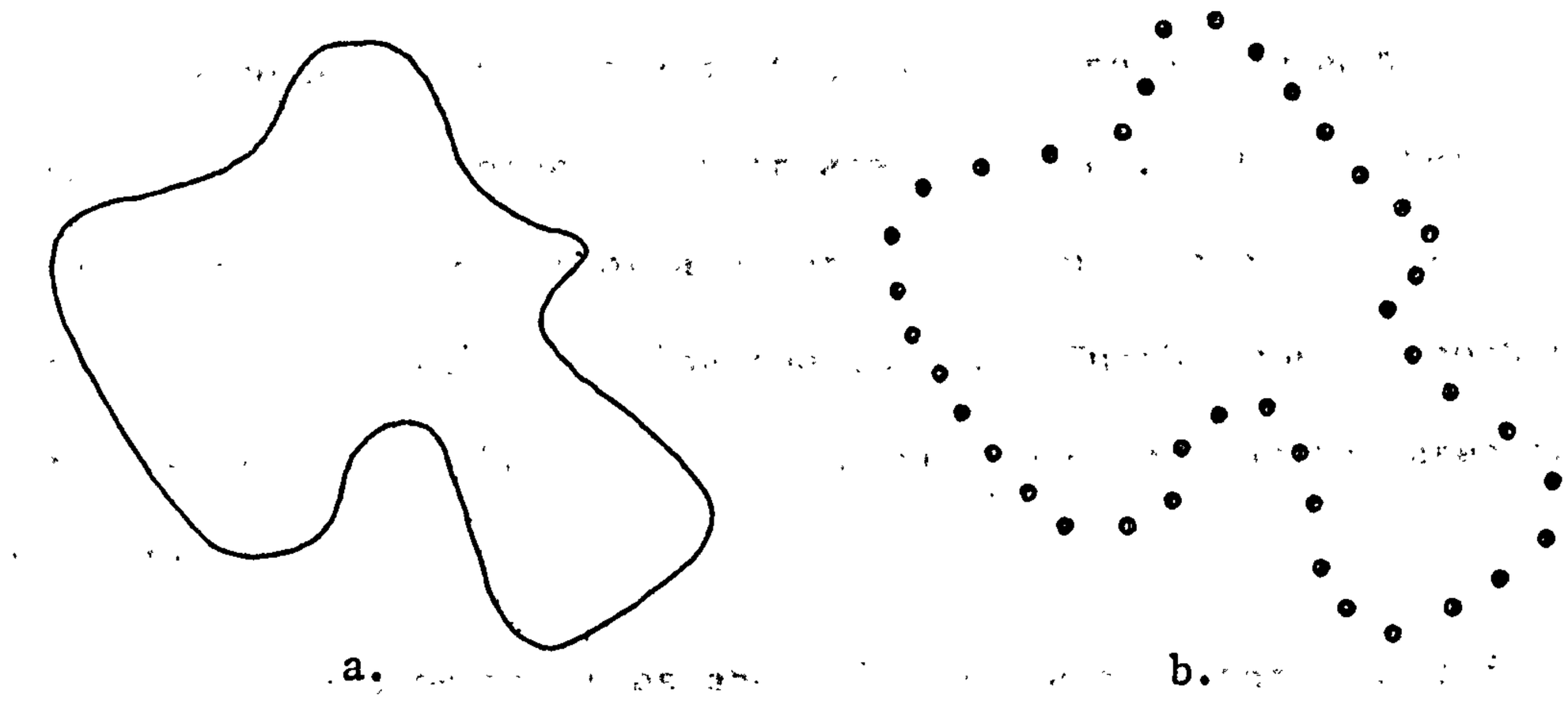
14.00 CONCEPTS FROM STATISTICS

14.01 Starting from a set of data which has not been organised numerically (raw data) the simplest degree of order in which it can be put is to arrange it in order of magnitude - ascending or descending. The difference between the largest and smallest numbers is called the range of the data. Large amounts of data can be arranged into classes or categories and the number of items belonging to a class or category is determined. Such an organization of data is known as frequency distribution or frequency table. Frequency distributions can be represented graphically by histograms or frequency polygons. These are the simplest ideas in statistical treatment but an extensive body of theory exists for the study of statistical order both in nature and society

14.02 The statistical approach to the description of forms has found a wide application in biology, geography, petrology and other fields in which the description of irregular shapes is the first and most important step in the search for order and meaningful classification. The use of statistics to describe spatial data and shapes is relatively a new field which can influence the way we con-

ceive of forms through numerical statistical descriptors. Relating shape and number is not a new type of transformation of physical entities into numerical ones but the level of aggregation and comprehensiveness of the statistical approach is particularly expedient.

14.03 A set of numerical data (for which statistical analysis can be applied) about a shape can be based on linear distances between a discrete number of points, surfaces or area units whose juxtaposition composes the shape. This can be illustrated by an irregular continuous shape which can be regarded as one and the same physical object or a set of points or objects in a given spatial distribution, e.g. the spatial distribution of settlements in a region.



a. b.

DIAGRAM 1.21

In diagram 121a the two dimensional form can be described by a set of points delimiting its perimeter, diagram 121b. An index which specifies this shape can be a function of the distances between one point and all the others. This can be stated as,

$$I = f \sum_{j=1}^{n} d_{ij}$$

where I = a form descriptive index

i,j = any two points in the set

d = distance between points

n = number of points

f = specifies that I is a function of $\sum_{j=1}^{n} d_{ij}$

Or, it can be a function of the distance between one point and all the others for the n points

$$I = f\left(\sum_{j=1}^{n}\sum_{i=1}^{n} d_{ij}\right)$$

14.04 The combination of the distances can also be through multiplication or any other appropriate operation. The number of the units, a product of it or a power of it can also enter the functional relationship defining the index. Further we can combine other aspects of the shape such as the perimeter and/or the area in the relationship.

14.05 From the possibilities above it can be seen that there is a wide range of combinations of the aspects of the shape from which we may evolve a numerical index of shape. There is, however, a fundamental difficulty in the statistical description of shape: the capacity to differentiate between different shapes. An important criterion that the descriptor should satisfy is that it should be unique in the sense that other shapes described by the same technique should have different value indices unless they are equivalent in every respect.

14.06 In a set of numerical descriptive indices the order, ascending

or descending, of the values of the indices should correlate with some desired aspect of the relationship between the shapes when compared. This aspect of numerical form description is illustrated by the work of Krumbien and Pettijohn[43]. They developed indices to describe irregular shapes. In these indices the area, perimeter, longest axis, diameter of largest inscribed circle and diameter of smallest circumscribing circle were used as parameters of the form to be described. They were combined and modified in such a way that they allow ready comparison with a circle. One such index relates the area of the circle that would be generated by the longest axis of an irregular shape to the actual area; and a circle would, therefore, have a shape index of 1.

14.07 Haggett[43] notes that measurement of shape involves other aspects of the shape that are not necessarily desired. Shape descriptors such as 'circular' or 'star-shaped' are limited in geometrical range and show strong operator variance in assignment . To overcome these difficulties Haggett suggests a resort to a method based on two theorems developed by Bunge . These are, a), any shape can be represented by a number of sides, which may be of any number but of equal length, and, b), if the distances between all vertices of the polygon are summed in a standard manner there exists just one set of sums that uniquely describes the polygon shape. To be able to compare shapes with each other and with other geometrical figures shapes can be measured in terms of the lengths of one side of the polygon which is taken as having a length of 1.00 .

14.08 The standard statistical parameters have provided concepts for the description of centrality and dispersion of spatial data and spatial distributions. The statistical measures of central tendency,

the mean, the median and mode have been translated into two dimensions to describe spatial distributions . The mean centre of a spatial distribution is the point where

$$\int R^2 . G(dA)$$

is minimum.

The median centre is defined as the point where

$$\int R . G(dA)$$

is minimum, where

G is the density of population over a very small part of area dA.

R is the distance from each part to the mean or median point in question.

14.09 Spatial distributions can be a continuous surface or a conglomoration of points depending on data and scale. Haggett[43] suggests that the measures of central tendency can be adapted to describe a cluster of points. In this way some areal statistical measures could be generalised to analyse continuous distributions. The most widely used statistical indices developed to describe spatial patterns are based on the 'nearest-neighbour statistic'. The nearest-neighbour statistic, R_n, is given by the formula

$$R_n = \bar{D}_{obs} / [0.50(A/N)^{-\frac{1}{2}}]$$

where $\bar{D}_{obs}$ is the observed mean distance between points and their

nearest neighbours.

A is the area

N is the number of points.

This index is in fact a measure of randomness. The distribution is random when the value of R_n is 1. The values of R_n range from zero, when the points are clustered together at one place, to 2.15 when the points are as far as possible from each other forming a regular hexagonal distribution .

15.00 STATISTICAL DESCRIPTION OF THE GEOMETRICAL PROPERTIES OF POROUS MEDIA.

15.01 In the branch of petrology concerned with the study of the physics of porous media, statistical measures of form are developed to describe the properties of a porous medium in connection with fluid flow. In these studies a close and an interesting analogy exists with built form and air flow in it. A built form corresponds to a porous medium where the existence of built structures (solids) and open spaces (voids) respectively correspond to grains and pores used to describe the solid and void components of a porous medium. In the following paragraphs the argument to develop a measure of form describing a porous medium is presented according to Scheidegger[46]. The presentation is close to the original since one only has to bear in mind an image of an urban structure and, reading through it, the development of the argument needs hardly any adaptation.

15.02 It is admitted, however, that there are problems of scale where the analogous properties of urban form and such porous media are in contrast. Another difference is that an urban structure is

open on the 'Sky-side' which changes the relationship between the fluid and the porous medium. The approach, however, is presented for its potential in offering an effective tool for the measurement of the most flow-relevant aspects of built forms: the structures and relationships between solids and voids.

15.03 Porous media are defined as solid bodies that contain pores. Although pores may be understood intuitively, it is difficult to give a geometric definition of what is meant by the notion 'pore'. Intuitively, 'pores' are void spaces which must be distributed more or less frequently through the material if the latter is to be called 'porous'. Extremely small voids in solids are called 'molecular interstices'; very large ones called 'caverns' and pores lie in between.

15.04 The pores in a porous system may be interconnected or non-interconnected. Flow of interstitial fluid is possible only if at least part of the pore space is interconnected. The interconnected part of the pore system is called the effective pore space of the porous medium.

15.05 The definition of a porous medium embraces a large class of media and therefore some sort of classification is convenient for identification. This classification is according to the types of pore spaces which they contain. A single porous medium may contain more than one type of pore class. Manigold[46] suggested a classification into voids, capillaries, and force spaces. Voids are characterised by the fact that their walls have only an insignificant effect upon hydrodynamical phenomena in their interior. In capillaries the walls do have a significant effect upon hydrodynamical phenomena in their

interior but do not bring the molecular structure of the fluid into evidence.

15.06 Pore spaces have also been classified according to whether they are ordered or disordered and according to whether they are dispersed or connected.

15.07 In this classification system it is clearly seen that there are some fundamental concepts which can be adapted to describe urban structure and others that are not suitable. A porous medium is characterised by a variety of geometrical properties. The fraction of void to total volume is important. This fraction is called the porosity and is expressed either as a frction of 1 or in percent. If the calculation of porosity is based upon the interconnected pore space instead of on the total pore space the resulting value is called effective porosity.

15.08 Another well defined geometrical property of a porous medium is its specific internal area. This is the ratio of internal area to bulk volume and it is therefore expressed as a reciprocal length.

15.09 The size of the pores in any one porous medium is an important geometrical property to measure, but since the pore system of porous media forms a very complicated structure difficult to describe geometrically it does not seem to be possible to find any simple parameter or any simple function to describe such structures .

15.10 The determination of the pore structure, therefore, is necessarily somewhat arbitrary, depending on what property of that surface one wants to describe; it will never be possible to encompass all its properties . According to Scheidegger,

"Intuitively, one would like to talk about the size of pores.

A convenient measure of the 'size' being the 'diameter'. The term diameter makes sense geometrically only if all the pores are of spherical shape - unless some further specifications are attached. If one has the flow of fluids through these pores in mind, it will not do to restrict oneself to spherical pores only (the latter would have no effective porosity at all); one would visualize the pores as rather tube-shaped things. One would then call the diameter of such a tube 'pore diameter'. Even this visualization of the term 'diameter' is geometrically quite meaningless unless the tubes are circular. In general they will not be circular and they will not even possess a uniform cross section since the walls will be irregularly diverging and converging. Thus one cannot even speak about a 'biggest' or 'smallest' diameter of the tube at any one point."

15.11 Scheidegger notes that there is no citation in the literature where this geometric dilemma has been satisfactorily solved. Nevertheless people talk about the 'size' of pores, 'pore size distribution' etc. without defining accurately what this is supposed to mean. A possible way out of the dilemma might be by defining the pore diameter (δ) at any one point within the pore space as the diameter of the largest sphere which contains this point and remains wholly within the pore space. Thus to each point of the pore space a 'diameter' could be attached rigorously. If desired, a 'pore size distribution' could be defined simply by determing what fraction α of the total pore space has a 'pore diameter' between δ and $\delta+d\delta$. It is easily seen that the pore size distribution thus defined is normalized in the following way

$$\int_{\delta}^{\infty} \alpha(\delta)\,d\delta = 1$$

Instead of dealing with α it will often be more convenient to deal with the cumulative pore size distribution, which will be denoted here by f; the latter is defined as that fraction of the pore space which has a pore diameter larger than

$$f(\delta) = \int_{\delta}^{\infty} \alpha(\delta)d\delta; \quad f(0) = 1$$

Once 'pore size distribution' is defined one can try to characterize it by certain parameters. This is best accomplished by fitting various standard distribution curves known from mathematical statistics to actual pore size distribution curves; the parameters of the standard distribution curves will serve as parameters for the pore size distribution curves. The simplest standard distribution curves suitable for this purpose are the various types of Gauss curves.[46]

15.12 In contrast to pore size distribution, it is easier to determine grain size distribution of a porous medium, at least if the latter is unconsolidated (dispersed). The grain size distribution as such does not mean too much as far as the properties of the corresponding pore space are concerned. In order to obtain correlations between grain size and pore size one has first to investigate the theory of packing of grains .

15.13 Another geometrical property has been proposed. This is termed tortuosity. Originally it was introduced as a kinematical property equal to the average relative length of the flow path of a fluid particle from one side of the porous medium to the other. It is thus a dimensionless quantity. The notion of tortuosity is somewhat doubtful .

15.14 In principle there are similar difficulties with the notion

of 'grain size' as exist with the notion of pore size. The grains are irregularly shaped and therefore their 'size' is not a priori defined. However, at least the concept of 'largest diameter' of a grain makes sense geometrically . An important difference here between grain size determination in porous media and urban structure is that in the latter the problem is, what aspect of the built unit dimensions to combine, in which orientation and at which 'distance' from the leading side of the area studied i.e. the windward side.

CONCLUSIONS ON THE DESCRIPTION OF FORM

The review of the potential concepts of set theory, group theory and statistics illustrates the richness of these areas as appropriate tools for form descriptors in an air-flow context. This may not come out immediately until one considers the size of information in investigations to be carried out. In this context the elegant format and compactness of set theory, which was originally adapted to a computer oriented form description, and group theory, basically used to describe crystal structures is particularly expedient. They lend themselves to describe economically large arrays of a linked progression of form aspects amenable to use in the one-to-one type of form-flow relationship. The set and group theoretic descriptors, however, are limited to forms which show a high degree of spatial order and regularity. Irregular forms, which happen to characterize most built forms, can best be described statistically. The geographer's approach to describe spatial distributions is a good illustration. The description of the form of porous media depends heavily on the statistical descriptor. Porous media in relation to fluid flow bear the closest analogy to urban

structures in relation to air flow. Therefore the descriptors of the former have a lot to offer as descriptors of the latter. This, however, has to be viewed against the differences in scale and flow media.

These possibilities, notwithstanding, point to a major research field, not only in air flow-built form studies but in the wider field of environmental design. It is suggested that more attention should be given to research in this area to overcome the present handicap manifest in the absence of appropriate form descriptors and tools to express them.

C H A P T E R I I

AIR MOVEMENT STUDIES

(A GENERAL REVIEW)

1.00 INTRODUCTION

1.01 The research into air movement and built form has concentrated mainly on indoor ventilation aspects. The physical processes involved, rates of flow and the effects of certain design features, are familiar themes in present air movement studies. This was done against the background of hygiene, comfort and economy requirements. The techniques of model simulation have also been investigated to establish the validity of such studies. In this chapter, a general review of these studies is given and, in conclusion, their usefulness as well as their drawbacks is assessed.

FULL-SIZE STUDIES

2.01 The general problems of air movement in indoor space have been studied by Daws.[76] The study analyses the requirements for indoor air movement and identifies them to be based on hygiene and comfort criteria. The hygiene criteria are those of odour removal and oxygen supply effected by fresh air changes. For oxygen supply, air flows of about 30ft^3/hour/person are considered adequate, while for the criterion of absence of disagreeable odours, larger requirements, approaching 15,000ft^3/hour/person, are indicated. Further observations include the diminution of the odour-strength as the cubic space available per person is increased, and that the efficiency of odour removal decreased as the fresh air supply is increased beyond 300ft^3/hour/person. The requirements for odour removal and the requirements for cooling or warming space via a natural ventilation system may be incompatible and the design of the system should take this into consideration.

The nature of the metabolism of the human body requires certain types of air movement based on the distribution of blood supply to the body, e.g., for comfort the head requires a somewhat cooler environment than the feet. The Thermal sense responds to the factors: air temperature, radiant temperature, air speed and humidity. Since discomfort may arise from warmer air near the ceiling region and cooler air near the floor region, lower air velocities are preferable in such spaces so as to allow the convection currents to control the vertical distributions of heat.

2.02 The paper describes the physical processes involved in ventilation as:

a) the action of the wind,

b) the action of buoyancy, and

c) fan action.

With respect to (a), on the windward surfaces pressure areas are created decreasing with decrease in the angle of impingement. In the surfaces parallel to the flow and those leeward to the flow suction zones develop. Pressure distributions are modified by the velocity gradient of wind with height and with design features such as projections and sharp corners. Three characteristics of wind affect natural ventilation:

a) wind pressure acts across the building so that the air enters at one surface and leaves from another;

b) the magnitude of the pressure difference is extremely variable requiring the adjustment of openings to control the flow, and

c) wind direction may alter from one minute to the next so that the direction of flow cannot be controlled.

However, where openings are available in one face of the building only, and cross-flow is prevented, pressure gradients along the face may still cause an air flow between openings and wind turbulence may cause pulsating

movements of air through the openings.

2.03 The second physical process involved in indoor air movement is due to the action of buoyancy. This occurs as a result of difference in densities of air inside and outside the building. It develops across the vertical distance separating inlet and outlet. It operates according to the relationship:

$$P_s = (\rho_e - \rho_i)gh$$

where P_s is the pressure difference due to buoyancy,

ρ_e is the external air density, ρ_i is the internal air density,

g is the acceleration due to gravity, and

h is the height between openings.

2.04 Although differences in density may be caused by variation in the proportions of the constituents of the air (e.g., water vapour and carbon dioxide) but temperature differences constitute most of the force due to buoyancy. When the temperatures are about $60^{o}F$ the pressure, expressed in inches of water, is approximately:

$$P_s = 2.8 \times 10^{-5} h(T_i - T_e)$$

where T_i, T_e are respectively the internal and external air temperatures.

2.05 This pressure acts vertically in the space and cool air enters the building through the lower openings and warmer air enters or leaves through the upper openings depending on the sign of the temperature difference. In general, buoyancy action can be overshadowed by wind pressure and it can only act in calm, warm weather.

2.06 The relationships determining air flow through a building tend to neglect air density on account of small temperature differences with which

air density is considered constant. Pressure differences across a building are small compared with atmospheric pressure. The law of continuity for steady flow requires that volume flow rates of air entering and leaving the ventilation space should be equal. Tests show that the static pressure loss across a ventilation opening is proportional to the square of the volume flow rate of air. Factors of proportionality depend on the type of opening and, to some extent, on the volume flow. The form of relationship, however, applies to cracks around the windows, doors and ducts. It also applies to flow through a thin plate orifice which for a coefficient of discharge of 0.65 is given by:

$$V = 1070\ \alpha\rho^{1/2}$$

where V is the volume flow rate (ft^3/hr),

ρ is the pressure loss (in w.g.), and

α is the orifice area (in^2).

2.07 For openings in parallel (on the same side of the wall) the equivalent orifice area is the sum of the individual equivalent orifice areas:

$$V = 1070\ (\alpha_1 + \alpha_2 + \ldots)\rho^{1/2}$$

For openings in series, the equivalent orifice is given by:

$$1/\alpha^2 = 1/\alpha_1^2 + 1/\alpha_2^2 + \ldots$$

2.08 The pattern of movement of air leaving a room is such that room outlets of small areas compared with room surface area are approached by air from all directions in quantities equal to the rate of air supply. The approach speed is larger near the opening and decreases in inverse proportion to a power of the distance away from the opening. The patterns further from the outlet inside the room are dominated by the action

of air entry and convection.

3.00 The B.R.S. paper 34[72] also outlined the physical forces responsible for air flow and natural ventilation in buildings, describing their processes and how to incorporate design features (openings, plan shapes, etc.) to benefit from them. The primary forces behind natural ventilation in buildings are identified as wind and stack effect. To utilise these forces in the ventilation of buildings appropriate designs are required for the openings, their size and position. These aspects provide the means of control of these forces. In addition, there is a limited control on the stack effect which depends on external temperatures.

3.01 In the case of the stack effect, it is the temperature differential between the inside and the outside of the building that is responsible for the movement of the air from the inside to the outside of the building. The rate of air change will depend also on the height between inlets and outlets and the size and design of aperatures. The external wind pressure at the aperatures of the stack system can encourage or oppose the stack effect.

3.02 In designing the aperatures for a natural ventilation system, it is suggested that consideration should be based on certain assumptions of the external conditions: the speed and direction of wind and the external temperatures. These design assumptions will obviously lead to undesirable conditions for part of the time, since they are based on average values. Deviation from these average values is sure to happen in cases of built-up areas or with the presence of plants and trees on the site. Due to these changing conditions, the study proposed that a scheme for natural ventilation should utilise both wind and stack effect if necessary.

3.03 The study suggests a method to calculate and indicate the likely air change rates due to wind and stack effects for simple cases, e.g., assembly halls and open single storey factories. In this method it is first necessary to:

a) assume the speed and direction of the wind.

b) decide which openings will act as inlets and which will act as outlets, firstly under the action of wind, and secondly with stack effect.

3.04 Assuming a rectangular plan of the building, wind direction normal to the inlet, equal areas of inlet and outlet, the rate of air flow in cubic feet per hour through the building is given by:

3150 x (area of inlet) x wind speed in miles
in sq. ft. per hour.

Adjustments to this expression are necessary when the wind direction is not normal and/or when the areas of the inlet and outlet are appreciably different. For a wind oblique at 45° a correction factor reduces the value of the above expression to 50%. For different areas of inlets and outlets, the figure 3150 is substituted for the appropriate value in table 2.1 below.

TABLE 2.1

Area of outlets / Area of inlets	Value to be substituted for 3150 in above expression	Area of outlets / Area of inlets	Value to be substituted for 3150 in above expression
1	3150	5	4400
2	4000	3/4	2700
3	4250	1/2	2000
4	4350	1/4	1100

3.05 To calculate the ventilation rate due to the stack effect for equal areas of inlet and outlet, the following expression is given:

the rate of air flow in cu.ft./hr. x 540 x area of inlets in sq.ft. x height in ft. between inlets and outlets x temp. diff. between inside and outside air in degrees F.

where areas of inlet and outlet are appreciably different, adjustment according to table 2.2 below is to be made.

T A B L E 2.2

Area of outlets / Area of inlets	Value to be substituted for 540 in above expression	Area of outlets / Area of inlets	Value to be substituted for 540 in above expression
1	540	5	745
2	680	3/4	455
3	720	1/2	340
4	740	1/4	185

3.06 In cold weather the air exchange between inside and outside may put a great load on the heating system by causing more loss of heat due to incoming cold air. The rate of heat loss for a given rate of air exchange can be calculated from equation:

Rate of heat loss (BThU per hour) = [0.019] x Rate of air flow (cubic feet) x Temperature Difference °F

In cases where air movement patterns and rates of air change are complicated by complex design and internal partitioning it is suggested that measurements on actual buildings should be made to estimate their ventilation conditions in various circumstances.

4.00 Dick[77] studied the fundamentals of natural ventilation of houses. The paper states some of the laws of natural ventilation in Daw's paper.

There is, however, a more detailed formulation of flow across apertures arranged in series. For two components arranged such that the air current traverses them successively, with equivalent areas α_1 and α_2 the flow equation may be written as:

$$V = 1070\ \alpha_1 H_1^{1/2}$$

$$V = 1070\ \alpha_2 H_2^{1/2}$$

where H_1 and H_2 are the respective pressure drops across the components. The total pressure drop, H, becomes $H_1 + H_2$. The rate of air flow expressed in terms of H becomes:

$$V = 1070\ \frac{\alpha_1\ \alpha_2}{(\alpha_1^2 + \alpha_2^2)}^{1/2}$$

From this equation, the equivalent area is given by:

$$\frac{1}{\alpha^2} = \frac{1}{\alpha_1^2} + \frac{1}{\alpha_2^2}$$

The implication of this formula for apertures in series in an air flow circuit is that the total effective area of such apertures is always less than either of the two separate areas.

4.01 The second part of the paper outlines the factors involved in air flow. Four factors are considered responsible for air flow with respect to structures:

1. wind.
2. heated flues.
3. stack effect.
4. fire-beds.

for which pressure differentials are given in table 2.3 below.

T A B L E 2.3

TYPICAL ACTING PRESSURES

Agency	Pressure Head (in w.g.)	Assumptions
Wind - exposed area	0.04	Velocity head at 8.5 mph
- built-up area	0.004	Effective wind speed reduced by a factor of 3
Heated flues	0.07	Flue 27 ft. high with temp. excess 100°F
Stack effect	0.01	Height 15 ft. with temp. excess of 20°F
Fire beds	0.015	Fire-bed 1ft. deep

4.02 Wind: exposed areas: the effect of wind on pressure patterns and distribution on a building skin was investigated by Irminger and Nøkkentved. They found that the pressures produced were approximately proportional to the square of the wind speed. Pressure distribution patterns change with changes in wind direction.

Built-up areas: there exists in built-up areas a shielding effect, which reduces the pressures on buildings due to wind.

4.03 Flue: the pressure due to heated flues depends on the difference in weight between the column of the flue gasses and a similar column of external air. The temperature of the flue depends on the appliance at its inlet. The rate of decay of temperature with height in the flue is determined by the mass flow of gas and the thermal properties of the flue and its surrounds.

4.04 Stack Effect: this is mainly due to the external/internal temperature differences of the outside and inside of a building. Its effect is not likely to be large in two storey buildings and is reduced with high external wind velocities. Pressure due to stack effect can be calculated from:

$$H = 7.6h \left(\frac{1}{T_e+460} - \frac{1}{T_i+460}\right)$$

where H = pressure (in w.g.)

h = height of effective column (ft.)

T_e = external temp. (°F)

T_i = internal temp. (°F)

For temperatures in the region of 60°F an approximation of the formula is:

$$H = 2.8 \times 10^{-5} h \left(T_i - T_e \right)$$

4.05 Fire-beds: for one foot deep fire-beds the pressure is 0.015 in w.g., or 1 ft. of air. This is an upper limit which cannot be exceeded no matter how high the temperature is.

4.06 The paper in its final section tabulates typical equivalent areas. Using measured flow characteristics equivalent areas for various building components have been constructed. Table 2.4 shows the various equivalent areas as derived from measurement or using free areas where such measurements are not available.

T A B L E 2.4

TYPICAL EQUIVALENT AREAS

Component	Equivalent Area (Sq. In.)	Source
Windows -		
unweather-stripped	13	25 ft. of crack - BRS data
weather-stripped	3	" " " " " "
Frame	1	Guide issued by American Society of Heating and Ventilating Eng. (ASHVE).
Doors -		
unweather-stripped	13	18 ft. of crack in poorly
weather-stripped	7	fitting door - ASHVE.
Walls - unplastered	3	9 in. walls, 100 sq. ft.
- plastered	0	ASHVE.
Air bricks	10-50	
Floors - solid	0	
- tongued and grooved boards	35	1/16 in. gap at skirting. Floor 12 ft. x 12 ft.
- square boards	200	1/16 in. gap. Floor 12 ft. x 12 ft.
- ventilators	40-90	Wall run of 60 ft.
Flues - open fire	50	
- gas fire	20-50	
Heating appliances	large range	
Ventilators -		
fixed louvres	24	12 in. x 3 in. ventilator - BRS.
constant flow	13.5	At 2 mph) B.R.S.
	3.5	At 20 mph)

PAGE

MISSING

IN

ORIGINAL

5.00 Approaches to the study of air permeability in inhabited premises were outlined by Pascal.[87] The infiltration of air through construction gaps in the windows and doors inside a building or on its skin can exert a considerable load on the heating of the building in cold climates. This is shown in table 2.5.

TABLE 2.5

Number of air changes per hour	Heating required (Q) Millitherms/hr.
0	585
1	960
2	1335
3	1710
4	2085

5.01 The paper outlines two approaches to encompass the various factors involved in determining the rate of infiltration (permeability of the windows and doors as a function of the pressure, wind pressure, arrangement of rooms, thermal ventilation).

a) an aggregate method whereby 'the renewal of air is determined for particular real cases and on the basis of many results an attempt is made to deduce a general law, and

b) an analytic method in which 'each process involved in the renewal mechanism ... is studied separately and the various results are then combined in order to solve a particular case .

As examples of the aggregate method the paper mentions the tracer gas technique using a Katharometer and a method based on the electrical

power consumption for heating. The analytic method comprises the study of the following parameters with a view to incorporating their appropriate coefficients corresponding to observed situation:

1. various types of joint;
2. size of joint;
3. air permeability of complete sashes;
4. wind velocity;
5. insulation;
6. pressure exerted on the building at different points;
7. type of building and situation;
8. type of premises;
9. thermal ventilation.

6.00 Tamura and Wilson[89] investigated the operation of the physical processes of ventilation acting through fortuitous gaps in two similar houses at different sites. The physical forces considered were natural wind, stack effect and furnace operation. In the summer it was found that leakage rates varied linearly with the wind velocity while the stack effect and furnace operation were responsible for the pattern and extent of air leakage. For one house the air change rate was found to vary linearly with the square root of the difference between inside and outside temperatures. It was also observed that the combined effect on air change rate of wind and temperature difference was less than the sum of either of them acting independently. The influence of furnace operation was quite marked on air leakage. In one house it was responsible for approximately 50% of the rate of air change and caused infiltration through the ceiling construction. The paper also points out discrepancies between winter calculation leakage rates (based on the ASHRAVE Guide and Data Book method) and measured rates amounting to a

difference in rates depending on indoor-outdoor temperature difference and on furnace action.

7.00 Dick[79] studied ventilation properties of occupied houses. He investigated the rate of heat loss in houses as a result of natural ventilation processes, i.e., wind pressure and pressures developed due to heated flues or stack effect. Two housing groups were the subject of the investigation. One group was on an exposed site in which the pressure head due to wind was twice as much as that in the second group which existed in a sheltered site. In the two sites the mean seasonal external air temperature was the same (42°F) but the mean seasonal difference between house temperature and outside was higher for the sheltered group (16°F; 14°F for the exposed group). Further information was obtained about the tenants' window opening habits and expressed as a mean number of open vents and mean number of open casements. The air change rates (expressed as changes per hour) were drawn for:

a) mean seasonal wind and temperature difference,

b) at fixed wind pressure, and

c) at fixed temperature difference.

Table 2.6 gives a summary of the relevant information and the findings of the study.

T A B L E 2.6

	Abbot's Langley (Exposed Site)	Bucknall's Close (Sheltered Site)
1. WIND PRESSURE:		
Exposure	Exposed	Sheltered
Mean seasonal wind speed	8.5 mph	4.5 mph
Direction of prevailing wind (WSW)	Normal to house front	Normal to house front
Pressure head produced across house with WSW wind	0.9 x velocity head	0.4 x velocity head
Pressure drop at respective mean winds.	0.032 in w.g.	0.004 in w.g.
2. TEMPERATURE:		
Mean seasonal external air temperature	42°F	42°F
Mean seasonal difference between house temperature and outside	14.4°F	16°F
3. TENANT WINDOW-OPENING HABIT		
Mean number of open vents (with house ranges)	1.73 (0.24 to 3.02)	3.06 (0.99 to 5.46)
Mean number of open casements (with house ranges)	0.23 (0.)6 to 0.77)	0.41 (0.12 to 0.73)
4. AIR-CHANGE RATES (CHANGES PER HOUR)		
a. For mean seasonal wind temperature difference	v = 8.5 mph ΔT = 14.4°F	v = 4.5 mph ΔT = 16.0°F
Closed house	1.51	0.88
Increase per open vent	0.46	0.28
Increase per open casement	0.65	0.56
Occupied house with mean site windows open	2.46	1.98
Range for individual occupied houses	1.6 to 3.1	1.0 to 3.0
Increase in site rates due to occupation	0.95	1.10
b. At a fixed wind pressure	0.032 in w.g.	0.032 in w.g.
Closed house	1.51	0.88
Increase per open vent	0.46	0.46
c. At fixed temperature difference	Flues and/or Stack (T= 14.4°F)	Stack (T = 14.4°F)

	Abbot's Langley (Exposed Site)	Bucknall's Close (Sheltered Site)
Closed house	0.87	0.84
Increase per open vent	0.23	0.27
Increase per open casement	0.33	0.54

5. HEAT LOSS RATES:

Weekly site rates	7.5 therms/wk.	5 - 9 therms/wk.

7.01 The findings of this investigation, the effect of the studied factors on the rate of air change and consequently on heat loss, coupled with the results of a regional survey of the temperatures maintained and the window-opening habits in local authority houses, were extended to other housing. 6 to 8 therms average heat loss per week from occupied houses was estimated, depending on the exposure of the site and on the air flow induced by the heating system. The corresponding air changes are between 2 and 3 per hour.

9.00 Carne[73] studied natural ventilation of unheated closed rooms, investigating quantitatively the relative efficiency of a wall grating and a flue as ventilators effecting air change in unheated closed rooms, i.e., rooms in which windows and doors are closed.

8.01 Two rooms having opposite aspects each fitted with a flue and wall grating were subject to 350 determinations of natural air changes over a period of five months (November 1938 - March 1939). The paper gives details on the rooms' structure, location and orientation. During the investigation the windows and doors of the rooms under observation were closed and only the wall grating and flue were open and none of the rooms were occupied.

8.02 The test method employed the tracer gas technique with carbon dioxide as the tracer gas. Samples of the air at four points in the room were taken at regular 15 min. intervals over one hour periods, immediately after the discharge of the carbon dioxide. Wind speed and direction were also measured during the tracer concentration measurements. Room and outdoor temperatures were also recorded at the same time as the test.

8.03 In each room, results were obtained for eight wind directions of which the velocities are grouped in ranges of 3 mph. Against each of the eight directions and velocity groups the rate of influx of air was given for a range of flue opening areas (nil, 13.5 sq.in., 17 and 50 sq.in.) and for a wall grating area of 50 sq.in. The effect of normal temperature differences was considered negligible compared with that of the normal wind.

8.04 It was found that for houses of similar conditions and provisions a chimney flue with base opening of 15 sq.in. is on the average as efficacious as a wall grating having a 50 sq.in. free area in facilitating natural air change in a closed unheated room. When windows and door are open in the rest of the house the ventilation effected by the flue remains constant and independent of wind direction. Using the grating for the same purpose and in the same conditions, the ventilation increases when the grating is on the windward side, but considerably less when it is on the leeward side.

8.05 To achieve a uniform natural ventilation with respect to all wind directions the paper concludes:

a) provision should be made for a flue extending beyond the

eddy motion zone in the wind stream.

b) an opening should be provided between the room and the well of the building (with respect to this particular building form).

c) an opening should be provided between the well of the building and the exterior of the building in each of two opposite walls of the building (with respect to this particular building form).

8.06 It was also found that there exists a definite and complex relationship between influx rate and wind velocity. This was interpreted and explained with the help of photographs of the flow patterns streaming past grounded house models. A theory was suggested to explain the broad features of the observations. This theory was based on the identification at relevant regions with respect to the particular form and the nature of wind pressures (positive or negative) and their combined action to effect flow in the influx circuit.

9.00 Van Straaten[90] investigated the ventilation pattern of three houses of similar plan types, but different roofing systems. One of them is roofed with corrugated iron roof and has a ceiling, the second is the same, but has no ceiling and the third is the same as the first but has a corrugated asbestos roof cover.

9.01 The standard adopted for ventilation is based on the concentration of odour and is taken as an air change of 15 cu.ft./min. per person. The house type investigated is assumed to have an occupancy rate of eight persons. Thus, the minimum desirable ventilation rate in these houses is taken to be 8 x 15 = 120 cu.ft./min. Since temperature differential

between indoor and outdoor and the speed and wind direction are the principal factors responsible for natural ventilation, these factors were measured simultaneously to determine their effect on ventilation. Ventilation rate was measured by means of the Kathotometer method using hydrogen as the tracer substance. In all cases all windows were closed. The houses existed in a fairly exposed site.

9.02 In conclusion for this type of house and the three roofing systems investigated, it is observed that:

1. due to the influence of stack effect, the relationship between air change rate and wind speed deviates slightly from a straight line, especially at the lower wind speeds.
2. with all occasional ventilation openings closed, wind direction as well as moderate temperature differences between indoor and outdoor air have very little influence on ventilation rate in this type of structure.
3. in ceilinged houses with a corrugated iron roof covering the ventilation conditions during most winter nights will not satisfy minimum requirements if the wind speed, as measured at a height of 5 ft. above ground level, is below about 5 or 7 mph, depending on whether the air bricks are open or closed respectively. It is further expected that the same would apply to any kind of ceilinged house, irrespective of the type of roofing material used.
4. if the beam filling and the air bricks are closed in unceilinged houses with a corrugated iron roof, the ventilation conditions will be more or less the same as those in ceilinged houses with all air brick openings closed. The opening of air bricks would also not improve the ventilation conditions

to the desired level.

5. in unceilinged houses with an asbestos roof the ventilation conditions are much better than in any of the other houses tested under the same conditions. The apparent critical wind speed below which the volume flow will not be in accordance with the minimum requirements was found to be about 4 mph as measured at a height of 5 ft. above the ground level. With the beam filling fully open in unceilinged houses with an asbestos cement roof, the ventilation rates are in excess of minimum requirements under all weather conditions, to such an extent that draughty conditions will probably be experienced during cold windy spells.

6. it is doubtful whether the use of a larger number of air bricks per house would improve ventilation conditions to the desired level, since, due to their relatively small effective area, air bricks only become effective at wind speeds in excess of the critical wind speed

10.00 Caudill and Reed[74] studied classroom geometry from the point of view of both air movement (patterns and velocities) and lighting. Measurements are taken as a percentage of an outdoor reference air velocity and full scale models are used. Working with two ceiling heights of rooms with the same size and proportional location of openings it was observed that ceiling height of a room has no effect on the patterns of flow of air inside the room. The shape of the ceiling does affect the air flow patterns somewhat, depending on the exact ceiling profile. The depth of classrooms has very little effect on patterns and speed of flow. For the same dimensions of rooms their rate of air change is inversely proportional to the depth.

10.01 When the openings are oriented such that air enters perpendicular to their plane, the length of the classroom has very little effect on the inside air flow. With oblique orientation of openings to the direction of flow there develops a wind shadow set up within the classroom. The longer the classroom the larger the area free of wind shadows.

10.02 The combination larger inlets and small outlets was found to produce very slow air movement. For a constant inlet size, the air flow increases as the size of the outlet is increased. A great contribution to the increase in air movement is to have openings to act as inlets and others as outlets.

10.03 The following cases concerning the position and size of openings were studied on a room 30 ft.^{2} with 10 ft. ceiling height constructed to revolve and be orientated in any direction.

Position and Size of Openings

1. Large high windows on one side and small low windows on the other with the wind blowing against the small low windows/equal size small openings on both sides: investigating these situations has shown that the speed will be greater when the outlet opening is larger.

2. Large high windows on one side and small low windows on the other with the wind blowing against the large high windows/large high windows on one side and small low windows on the other side with wind blowing against the small low windows: investigating these situations has shown that in the case of unequal openings with different relative locations when the wind is reversed both speed and pattern of the air flow will change materially.

3. Equal size small openings on both sides/equal size small openings on both sides but higher: the location of window openings in the wall, particularly the inlet, greatly affected the interior pattern.

4. Maximum size opening on both sides unilateral openings: in order to provide movement of air through a room, there must be outlet openings as well as inlet openings.

5. Large high windows on one side and small low windows on the other with the wind blowing on the small low openings/maximum size openings on both sides: greatest speeds are obtained with outlets larger than inlets but the greatest volume of air flow is obtained when both inlet and outlet are maximum. When there is a stream of air flowing across the room, generally all parts of the room have some flow of air caused by the eddies adjacent to the air stream; but the eddies cause only very low speeds.

10.04 The way wind flows through an opening can be greatly influenced by introducing or taking away an overhang. Whether or not air will flow through clearstory windows above large overhangs (as in outdoor corridors) will depend on such factors as the slope of the overhang, depth of overhang and size of facia as well as the height of the window opening. Overhangs protecting vision strips in conventional glass block fenestration tend to divert the air upward through a simple opening into a classroom unless provided with slots.

10.05 The air flow pattern within a classroom is determined not only by the direction of the wind, but in the cases of simple window openings by the position of the opening in the exterior wall. When air flows against

the exterior wall of a classroom, it tends to flow over or around the building in a pattern parallel to the walls causing force components. These components help to determine in what direction the air will flow through an opening in the wall.

Strip windows have an advantage over the punched hole type because they allow evenly distributed air flow over the length of the classroom. Regardless of the location of the outlet, the air pattern within a classroom is determined by the type and location of the inlet.

Windows, through their pivoted position, are able to influence the horizontal pattern of flow. A horizontally pivoted window causes air to flow overhead or towards the floor of a room, depending on the angle of its opening and projection.

MODEL STUDIES

11.00 The studies reviewed so far are experimental, either concerned with physical processes or full scale studies of design and construction aspects of ventilation and air change. The following sections will present another approach in air movement studies. It is based on scale models and simulation which allow a certain degree of control of the conditions in which the investigations are carried out.

11.01 Smith[88] studied the feasibility of using models for pre-determining natural ventilation. It is noted that before models can be used with confidence for predicting flow the following aspects should be considered and information concerning them should be available:

a) size of models and corresponding air speeds, necessary for giving accurate predictions of air flow patterns and relative air speeds.

b) methods which can be used to determine air flow patterns in and around models.

c) methods which can be used to measure air speeds in and around models.

11.02 The main problem in model studies of air flow is the scale effect, since models are small-scale replicas of real buildings. In aerodynamic theory a model should give the same air flow pattern as a full-size building, provided that "Reynold's Number is the same for the model as for the full-sized building".

11.03 Reynold's Number is the ratio between the product of air speed v, air density ρand some dimension h,to the viscosity of the airμ, and can be stated as:

$$R = \frac{vh\rho}{\mu}$$

From this relationship it is important in model studies that the smaller the model the higher the air speed required to produce similar patterns of flow to those of the full-size building for constant air density and viscosity.

11.04 In air movement studies high speeds are expensive to produce and require relatively strong models, and small models are inconvenient to take measurements around. In the case of interior measurements, small models make it impossible to take such measurements. Smith notes that there is a definite possibility that appreciable changes in patterns are not likely to occur over a considerable range of the product of speed by the aerodynamic radius of the model, r_a, The aerodynamic radius is defined as:

$$r_a = \frac{2A}{P}$$

For a model of height h and length L, A is the product hL and P is the sum 2h+L.

Smith found that for:

$$2000 \leqslant \frac{2A}{P} v \leqslant 12000$$

models produce patterns of flow comparable to those of full-scale buildings. For models tested with values between 2000 and 12000 of $\frac{2A}{P}v$ there is consistency with results obtained from full-scale buildings for which $\frac{2A}{P}$ v is in the range 2000 - 125000.

12.00 Wannenburgh and Van Straaten[93] investigated the feasibility of employing model buildings in studies to predict the air flow characteristics of full-scale buildings. They studied the nature and characteristics of the stagnant zone above the pitched roof of a model classroom. Using a 1/12th scale model provision was made for changes in certain dimensions: wall or ceiling height, roof pitch and type of window. No consideration was taken of the orientation and aspect ratio and the model was contained by two perspex plates at the sides parallel to the flow. In this way, only two dimensional conditions were simulated approximating the model to an infinitely long building. Static tappings for pressure measurements were provided in the roofs and the windward and the leeward walls of the model.

12.01 Tests were carried out in an open jet wind tunnel of wind speeds between 5ft./sec. and 30ft./sec. Pitot static tubes were used for wind speed measurements and a yawmeter to trace the direction of flow.

12.02 The first set of observations in this study was concerned with the distribution of the static pressure on the walls and roof of the structure. For a 35° pitch roof, the largest depression, negative pressure, was towards the windward eave, proceeding to a positive pressure further

along the windward pitch before dropping to a negative pressure shortly before the ridge. The leeward pitch of the same roof and the leeward wall maintained a constant negative pressure value. The windward wall sustained a positive pressure value and the pressure difference across the model was estimated to be about 2.2 to 2.3 times the wind dynamic pressure.

12.03 For a 10° pitch roof a constant negative pressure prevailed. A constant negative pressure also prevailed on the leeward wall while the windward wall was constantly under a positive pressure value. The pressure difference across the model, however, increased to a value between 2.4 to 2.5 times the wind dynamic pressure. The authors concluded from these observations that, provided that the areas of ventilation openings remain the same, slightly better ventilation conditions can be expected in buildings having low pitched roofs. Further, it was concluded that since low pitched roofs are more or less always under suction such roofs are more suitable for a natural ventilation scheme in which the building is ventilated through suitable ceiling and roof openings.

12.04 Two observations were pointed out when two variations were made in the condition of the test. The two variations were:

a) opening the windows, and

b) removing the plates from the sides of the model, thus introducing three-dimensional conditions instead of the previous two-dimensional conditions.

Opening the windows produced no significant change in the pressure over the leeward side of the roof, but markedly decreased the absolute value of the depression on the windward side of the pressure, reaching a pos-

itive value sooner and remaining positive over a longer portion of the roof. Removing the plates decreased the windward wall pressure by about 49% and the leeward wall depression by about 8%. This resulted in a total reduction of pressure difference of 57% across the model.

12.05 The investigation established the shape of the stagnant zone over the 35° and 10° pitched roofs. It was observed that for both roofs the shape and height of the stagnant zone is the same up to the point where the flow retouches the 35° pitch roof and becomes modified in direction by the profile of the roof. It was then suggested that where the roof profile does not at any point intersect the zone streamline, i.e., the line demarcating the stagnant zone, the height of the streamline at the ridge will not be dictated by the pitch. This condition was found to be satisfied by a maximum pitch angle of 25° for a wall height of 15 in. However, the depression in the stagnant zone was found to increase with an increase in wall height, or with a decrease in roof pitch, and is very little influenced by roof overhang. The roof overhang affects greatly the velocity and direction of the air flow above the ridge, as well as the height of the stagnant zone above the ridge.

12.06 The practical use of the existence of a stagnant zone has been suggested as its potential for the location of roof ventilators, chimneys or other ventilation openings where effective ventilation can take place as a result of the pressure gradient across the openings of the device.

13.00 Givoni,[80] using scale models and a wind tunnel, investigated five problems related to an isolated room:

1. effect of outdoor velocity upon the average indoor velocity.
2. effect of window size, both for inlet and outlet openings.

3. effect of cross ventilation.

4. effect of outside wind direction in relation to the location of the windows.

5. effect of the number of inlet and outlet openings.

13.01 The tests were carried out on a model of the room of dimensions 65 x 65 x 50 cm. A wind tunnel of the open throat type was used. Measurements were taken at twenty-five points of a horizontal plane 12.0 cm. above the floor. Measurements of the velocity were taken to be a function of the resistance differential of two coils of resistance wire, one kept at air temperature and the second heated by a constant current with its temperature changing according to the ambient air velocity. By shaping the sensing elements into a conical spiral, directional effects were avoided and the average velocity was taken for a small region rather than at a point.

13.02 The range of opening sizes varied from $^1/3$ to full wall width at a sill height of $^1/3$ that of the wall. Various combinations of inlet and outlet sizes were studied. Outlets of various sizes at adjacent walls have also been studied. Wind direction was, in one case, normal to inlet, and in the other oblique at 45°. The comparative measure for the various arrangements was the average velocity averaged from the readings of the twenty-five points.

13.03 The main conclusions drawn from the study were summarised as follows:

1. the effect of window size above a certain minimum value was found to be small. Increasing the size of the inlet or outlet while keeping the other constant had a negligible effect.

Increasing the size of both inlet and outlet had some effect but the increase in internal air velocity is much smaller in proportion to the increase in opening area.

2. the effect of cross ventilation at constant total opening area was found to be quite considerable. The average internal air velocity was about 2.5 times higher in a room with two windows, one upwind and the other downwind, than in one with one window or two windows on the same side, of the same area.

3. the effect of wind direction was found to depend upon the relationship between wind direction and the axis through the opening. With the windows opposite one another, internal air velocity was higher for the oblique than for the perpendicular wind. With the windows in adjacent wall, the internal velocity was higher for the perpendicular wind. It seemed that with the wind parallel to the axis of the windows, the flow of the outside air occupies a smaller portion of the room space than when the wind has to change its direction.

13.04 In the second part of the study, the possibility of providing cross ventilation for a room with only one wall to the outside was investigated. It was found that provision of cross ventilation in rooms having one side exposure was effected by providing an air passage through a double ceiling ending in a fanlight. It was found that this method results in very great improvement in ventilation conditions. The efficiency of the method depends largely upon the details, mainly upon the opening angle of the fanlight. The location of the outlet opening has only a small effect and that of the size of the air passage was also small relative to the changes in size.

14.00 Givoni[83] in another study investigated a range of design problems from the point of view of ventilation. Some architectural design features and building elements such as vertical projections, indoor partitions, etc., are investigated to see their effect on the distribution and average velocities of a single room with openings only on one side. The effects of layouts and spacing of rows of buildings were studied with a view to their effect on indoor air movement of a room. In a third section, the effect of ventilation patterns on indoor temperature was also investigated.

14.01 In the first part, concerned with the architectural design elements, the objective was to create pressure gradient with the contribution of these design elements, thus enhancing the ventilation conditions of a single room with only one side containing openings. The elements investigated were vertical projections and balconies. It was found that providing the room with two windows each of which is flanked by a vertical projection from the internal side, a pressure region is created at the upwind window (wind being oblique) and a suction region in front of the rear window. This has the effect of drawing the air from the pressure zone to the suction zone, causing the air to enter through the foremost window, circulate in the room and finally exit through the suction zone. In this way, cross ventilation is effected and the average indoor velocities achieved values equitable with those of rooms having openings in more than one wall. With balconies, however, similar effects were achieved except that the pressure gradient was reversed, thus inlet and outlet were interchanged.

14.02 The vertical location of the window, its hinge position and opening angle have been investigated to examine the effects of these features

on the pattern of air flow and velocity distribution on zones below the window sill. A model room of 65 x 65 x 50 cm. dimensions was used for the investigations. Two such zones were taken at planes 0.15 and 0.30 of the height above the floor. Point velocities (at points $^{1}/10$, $^{3}/10$, $^{5}/10$, $^{7}/10$ and $^{9}/10$ window width units distant from the inlet) were taken. In all cases the window height was $^{1}/3$ that of the wall and extended the full width of the wall. Windows were horizontally pivoted with upper, middle and lower hinges.

14.03 It was concluded from this part of the study that altering the height and the angle at which the window is open affects primarily the pattern of flow and distribution of velocities of different points, but the effect on average velocity is more limited. Changing the angle of the sash to direct the flow downwards increased greatly the air speeds at points located in the path of the mainstream, but the air motion at the other sections of the room, induced by the air turbulance produced by the mainstream are not affected greatly.

14.04 The effect of flyscreens and the combined effect of flyscreens and balconies on internal velocities was examined. A block of three room units (each of size 30 x 30 x 30 cm.) was used and the measurements were taken for the central unit. Openings $^{1}/3$ the wall area were provided on two opposite sides. In one set, one opening is centrally located and in the other, two openings of the same total area as the first were laterally located. Flyscreens were either absent, on inlet, or on both inlet and outlet. In a fourth arrangement, a flyscreen was installed in front of the inlets and covered the whole of the balcony opening. Wind directions were perpendicular to inlets in one series, and oblique at 45° in another. The main conclusion drawn from this investigation was that

the screen had much more reduced internal velocities with an oblique wind than with a perpendicular wind, but the effect was much less when the screens were placed against the balcony openings, leaving the inlets themselves clear.

14.05 In a building a courtyard is provided, among other reasons, to give a measure of ventilation for spaces opening into it. The study looked at such a design with a view to establishing the effect of 'opening' such a courtyard on internal velocities of rooms abutting onto it. A four-room arrangement in a cruciform plan enclosing a courtyard was used. Two degrees of exposure of the courtyard were designed: completely open from the four sides (building lifted on stilts) and open from one side. Again, wind direction was either perpendicular or oblique, towards the opening or from the rear when the yard is partially closed. Observations in this part of the study point to the fact that the internal air velocity in rooms located on the leeward side of the yard was much poorer than on the windward sides, and the internal yard did not significantly improve conditions. It was found that best ventilation conditions in these leeward rooms were obtained when the building was raised on stilts, leaving the yard open to all sides. Less satisfactory conditions were obtained when the yard was partly or fully closed at the ground floor.

14.06 One of the ventilation problems of space partitioning is that such a partitioning may give two spaces, one of them upwind and the other downwind, with a marked reduction in air speeds for one or two of the subspaces. This problem was studied with a view to determining the relative sizes of the subspaces in relation to their location with respect to the inlet and, secondly, to examine the relative location of the partition with respect

to the openings and, thirdly, the relative disposition of the inlet and outlet in such a partitioned space. A model room 65 x 65 x 50 cm. with inlet and outlet sizes of $^1/3$ of the wall width, placed at $^1/3$ of the height was partitioned in a number of ways and air velocities were taken for two window dispositions.

14.07 The results show that the subdivision of the internal space caused some reduction in the internal velocities when the partition was installed nearer to the inlet window and in front of it, the average velocities were lowest, and better conditions prevailed with the partition nearer to the outlet. In such a partitioning system, it is preferable for the upwind room to be the larger one.

14.08 In the second part of the study, some of the town planning and layout features were investigated as to the potential of their configuration for ventilation of indoor spaces. The town planning elements of such signigicance were conceived in the study as follows:

1. direction and effective width of the main and secondary streets with respect to wind.
2. distance between buildings along the street.
3. general height of the building.
4. presence of high rise buildings among lower buildings.
5. layout of building blocks.

14.09 Investigations dealt with the effect of distances between rows of buildings, and effects of air flow restriction on ventilation conditions and flow and velocity patterns around the rectangular courts. Tests were made on model blocks of 60 cm. long, 30 cm. high and 20 cm. deep. The first series of tests considered the effect of distances between rows

of buildings and blocks in the rows. It has been found that with the increase of the distance between two rows the internal velocities in the second row decreased to a certain minimum and then increased rapidly with distance. The effect of increasing the spacing between blocks in the rows was such that the internal velocities increased to a certain maximum and then decreased with increasing separation.

14.10 The second series dealt with the restriction of the air flow between building blocks in order to augment pressure gradients across the blocks. This series of tests concluded that by alternate blocking of the wind flow between parallel building blocks, it was possible to improve on the ventilation conditions in free-standing parallel blocks. By varying wind direction, these ventilation conditions were less varied.

14.11 The third series in the tests examined the indoor air velocities in rooms around a rectangular court. The internal air speeds in the leeward rooms were found to be about one third to one half of the speeds in the windward rooms and the directions opposed to that of the external wind.

14.12 In the third part of the study, the effect of ventilation on internal temperature was examined in a number of thermal models with walls built from a range of building materials (concrete, hollow concrete blocks 20 cm. thick, fireboard curtain walls). In each model, the roof was made of 50 mm. thick expanded polystyrene enclosed in two sheets of asbestos cement 5 mm. thick and whitewashed. External colours of the walls were either grey or whitewashed. The internal temperatures taken were the internal air temperatures and the surface temperature, taken at the surface of the wall. Outdoor measurements were those of the air temperature

and the solar radiation impinging on a horizontal surface.

14.13 It was found in this part that the effect of ventilation on indoor temperatures depended on the materials, and particularly on the external colour. With a white exterior, daytime ventilation elevated the indoor temperature, an effect which increased with the thickness, thermal resistance and heat capacity of the walls. When the exterior was dark, daytime ventilation reduced the indoor temperatures.

15.00 The study of air movement around buildings and in open spaces received relatively little attention. One of the first of such studies is by Evans. He proposed that if planners are to incorporate the beneficial aspects of wind flow into their designs and eliminate its undesirable aspects, they must know:

a) what the general air patterns around a proposed building will be.

b) where the eddy areas will be.

c) the pressure distrubution around the building.

Evans[96] investigated the extent of the eddy zones (areas around the building which do not receive the direct full force of the oncoming wind) on the leeward sides of a variety of building forms. The study of air movement in relation to built form is made particularly difficult by the number of parameters which have to be included. In the preliminary design stages, Evans suggests that the relative importance of air flow control should be determined, followed by simple but thorough model testing for determining, prior to construction, the behaviour of the air flow to be experienced.

15.01 Sexton[97] discusses the importance of pressure distribution on a building in relation to rain penetration. By using existing data, pressure

differences across walls of buildings can be calculated. The pattern of air flow around buildings determines the way in which rain impinges on their surfaces.

15.02 Wise[98] reports on a series of investigations of typical town centre developments in which a problem of wind environment has arisen. From a series of model tests and full scale measurements, the paper comes out with some general ideas on design for outdoor wind environment and suggests a method of approach for planners and designers. The architect and planner need meteorological information and comfort criteria as well as aerodynamic data for the design and layout of groups of buildings in towns. Wise urges more work in the field of presentation of relevant aerodynamic information in a form suitable for design use. The work at present is concerned with mean velocities but the effect of turbulence is recognised.

CONCLUSION

This general review of air movement studies in relation to built form has been concerned with main themes and techniques in current research. It aimed at laying emphasis on prevailing approaches and, as such, to highlight the problem areas that investigators have thought worthy of investigation. Such problem areas come under the general theme of ventilation and air leakage in relation to certain design features. Other studies attacked the problem of outdoor air movement. But these are very limited in range and depth. Air movement studies have, therefore, shown more interest in indoor air movement than in its outdoor counterpart.

PART II

MEASURES OF WIND

C H A P T E R I I I

THE DEVELOPMENT OF A QUANTITATIVE VISUAL FLOW DESCRIPTION

1.00 INTRODUCTION

1.01 An important aspect in the study of wind flow in relation to built form is the shape of flow. The description of this aspect and its relationship to variations in form would provide the designer with a fundamental basis for evaluative and comparative studies at preliminary and advanced stages of the development of his design. To describe the flow in concomitant visual and quantitive media supplies valuable information for the urban landscape designers, urban designers and architects. The location of plants or plant beds, of open movement corridors or the disposition of activitity locations indoors or out are all design aspects that can benefit greatly from such form-flow description. It is, therefore, imperative for the wind considerations in the design of built forms to study form-flow relationships in a visual qunatitative approach.

1.02 There are infinite variations and combinations of forms. Each arrangement may have its characteristic corresponding flow shape which varies from others, either in values or in spatial patterns, or both. Due to this, the study of form-flow relationships in this context is confronted with the problem of massive information. It renders it unusable for such information to be in a large impractical format. It should, therefore, be condensed in such a way that the final product is practical for use by designers and meaningful in terms of form-flow rleationships. This chapter purports to develop a form-flow descriptor based on quantitative and visual information incorporating suggestions for the contraction of the ensuing large body of information.

EXPERIMENTAL SET-UP

2.01 A large number of simple model arrangements were studied in a wind

tunnel. The experimental set-up comprised

a) the wind tunnel:

an open jet type wind tunnel is used. It has a working section of 1.50 x 2.00 m. Speeds used were about 8 - 10 m./sec.

b) the anemometer:

a DISA hot wire anemometer with directional probe was used.

c) the models:

wooden blocks of square cross-sections were used. The scale of the blocks was 1:50 corresponding to single storey buildings. Each arrangement comprised two such blocks laid parallel to each other. Measurements were taken in the space in between (diagram 4.1). There were ten different space sizes, twenty different block lengths and three orientations (diagram 3.3).

2.02 The hot wire anemometer used for flow measurements is directional. This meant that the anemometer measures only a velocity component perpendicular to its length. Great difficulty was met in trying to ascertain the orientation of the probe wire to measure velocities near the models. Away from the models, a sample with the probe in any orientation produced more or less the same average velocity within +/- 3% of the sample taken when the probe wire is parallel to the block length. This is largely due to the turbulence in the flow and the variability in its direction at any particular point of measurement. The velocity at any point is taken as an average of 5 - 10 readings at that point. The larger sample was necessary where the flow shows high turbulence, particularly in the case of the short block lengths with large spacing and oblique orientations.

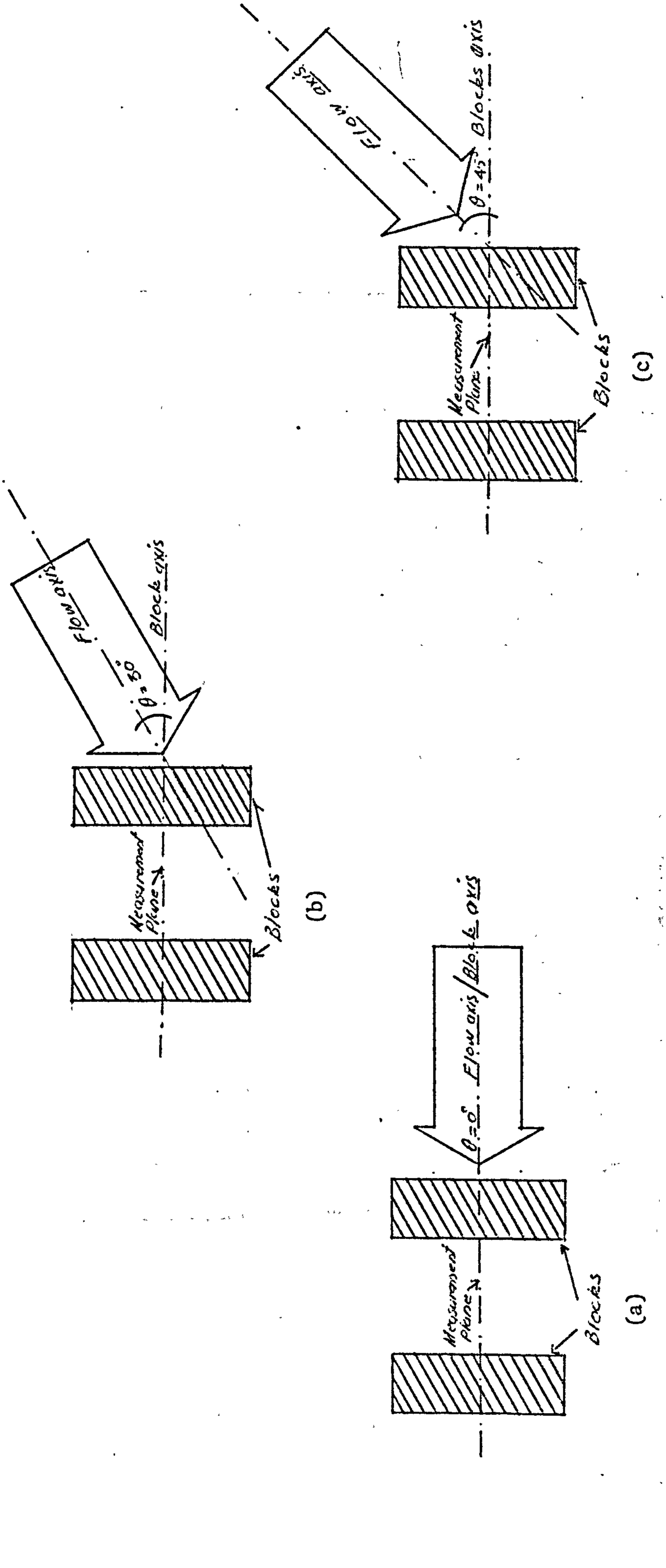
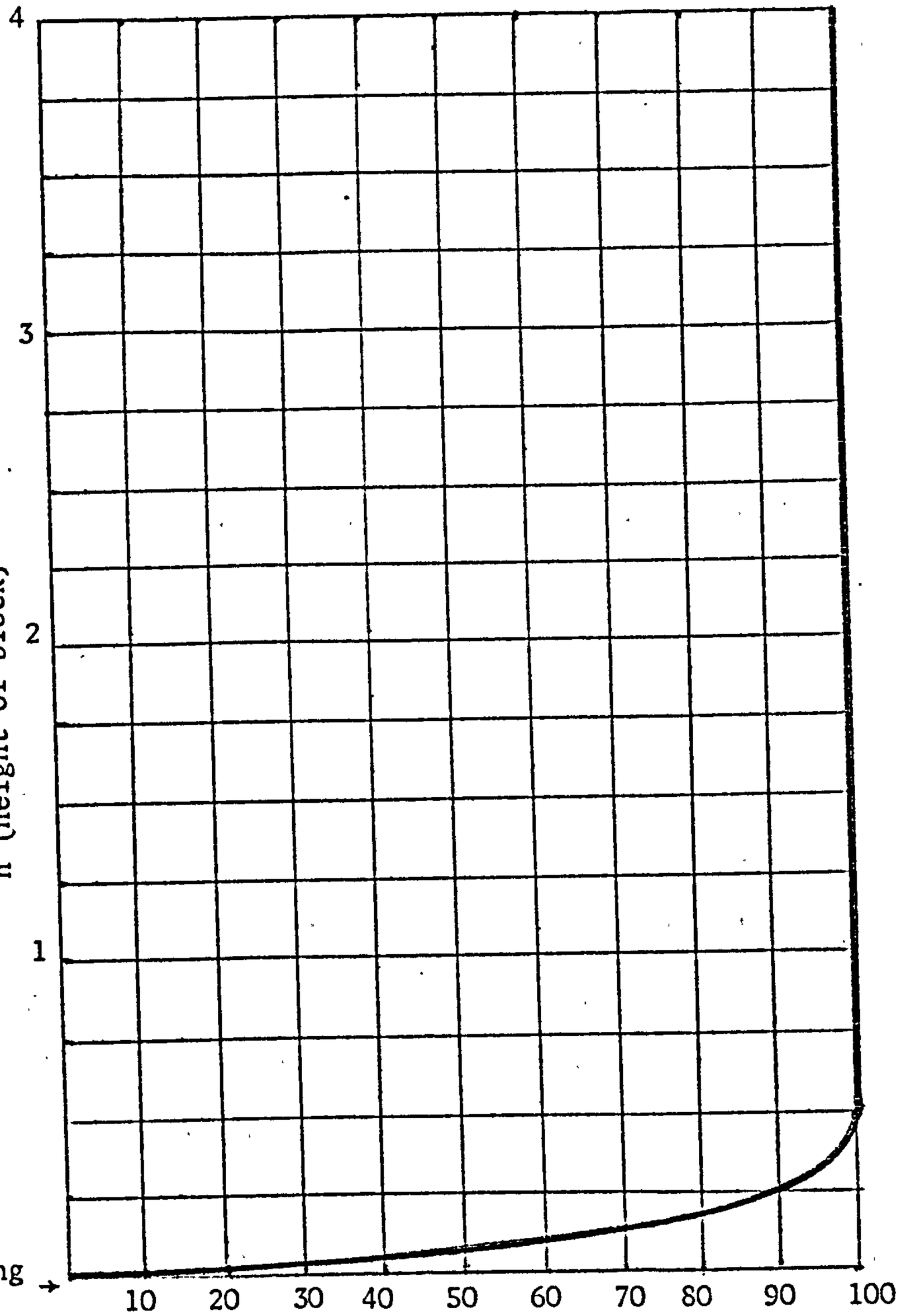


DIAGRAM 3.3: ARRANGEMENTS OF BLOCKS IN DIFFERENT ORIENTATIONS



$$V = \frac{V_h}{V_c} \times 100$$

DIAGRAM 3.4: WIND PROFILE OF WIND TUNNEL.

2.03 The tunnel gave a uniform flow for the greater part of its vertical section, but there was a wind profile due to the floor of the working surface. Diagram 3.4 shows the tunnel wind profile relating the height to the speed. The speed at different heights is expressed as a percentage of the speed at the centre of the vertical section in the centre of the working section. This is given by:

$$V = \frac{V_h}{V_c} \times 100$$

where V_h is the speed at height h.

V_c is the speed at the centre of the vertical section of the tunnel.

V is the normalised speed at the relevant point.

MEASUREMENTS AND FLOW REPRESENTATION

3.01 Measurements were taken at points arranged in a grid in the central vertical plane of the space between the blocks. A typical grid of measurements is shown in diagram 4.1. The measurement points of the grid are arranged at 1 unit distances horizontally, and about 1/4 unit vertically. The number of points in any given horizontal plane depends on the space size. For spaces 1 and 2 there are three points of measurement at each horizontal plane: 2 points close to the blocks (8mm. approximately) and the third point located centrally within the space. For spaces 3 - 10 the points are arranged at 1 unit distances with two points 8 mm. from each block. Vertically, measurements are taken at 7 levels, i.e., the highest plane of measurement is about 1 3/4 units high. This was considered sufficient to indicate the patterns within the space. The flow velocities above this level reach the free flow value, i.e., levels where the presence of the obstacle (the models) has

no significant influence on the flow.

3.02 The velocity at any point is computed from the following formula and presented as a percentage of free flow reading:

$$\left(\left[\frac{\sum_{i=1}^{10} V_i}{i} \right] / V_f \right) \quad \times 100$$

where V_i is the reading of the digital voltmeter.

i is the number of readings taken at the point.

V_f is the free flow reading taken at a level equal to twice the height of the block before placing it.

3.03 The grid of measurements provided the basic data for the interpolation of the speed contours. When those were completed, for any arrangement, they gave the quantitative visual representation of the flow. The interval of the interpolated values is 5%, i.e., the difference in the speed values between each two successive speed contours is 5%.

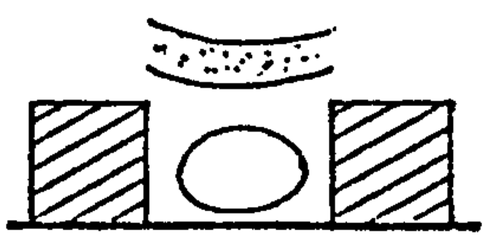
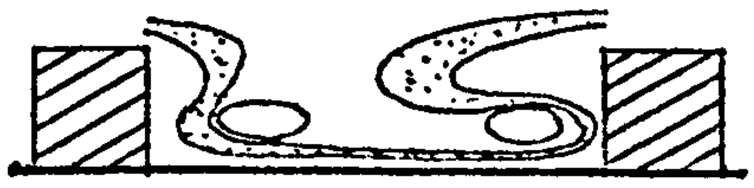
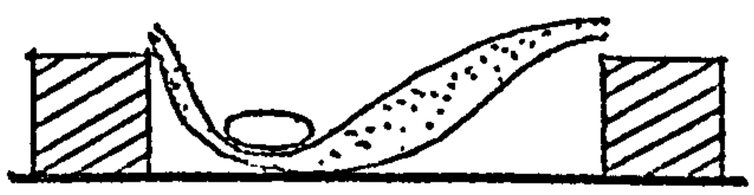
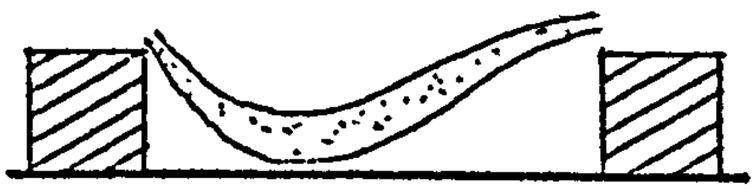
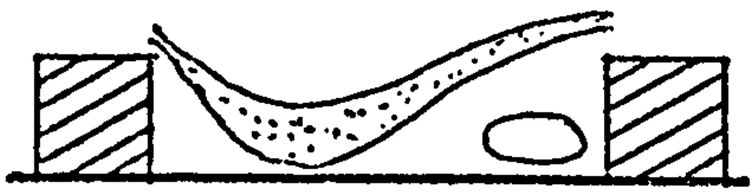
3.04 By its very nature, the quantitative visual representation of the flow patterns calls for a pictorial sequence in the cases studied following the changes in the form aspects: block lengths, space sizes and orientations. This is bound to produce voluminous visual material as the following 50 diagrams, with 10 figures each, will show. If no method for meaningfully contracting this material, without substantial loss of information, is available, the usefulness of such material can hardly be appreciated where it is most needed: design decision situations. As an easy access to such material in a design situation, it should be easy to read through and the characteristics of flow patterns must stand out. The choice of a medium for the presentation of quanti-

tative flow patterns of a range of forms depends on whether the forms change progressively (in this study this is the case where changes in the form aspects are multiples of a basic unit). The progressive change in form aspects permits speculation on the existence of a functional relationship, in a mathematical sense, between the form parameters and the flow patterns. This, however, requires the mathematical representability of the flow patterns in the first place. If such a functional relationship exists, then the mathematical representation is the best form of contracting this pictorial information. From such a representation the pictorial form of the flow can always be retrieved from the mathematical function.

3.05 This approach, however, is fraught with difficulties and it assumes a mathematical skill beyond the training of the potential users: the designers. Such is an important consideration if studies of air movement in relation to built form are to serve design in a readily usable format. Therefore, it is suggested here that this could be achieved by a combination of a 'catalogue' format showing the flow patterns with comments on significant developments and a 'morphological summary' showing the broader features of form-flow pattern relationships, and a general discussion bringing out relationships and observations which were possible to reveal neither in the catalogue nor in the morphological summary. This scheme is followed here, and two examples of morphological summaries are given.

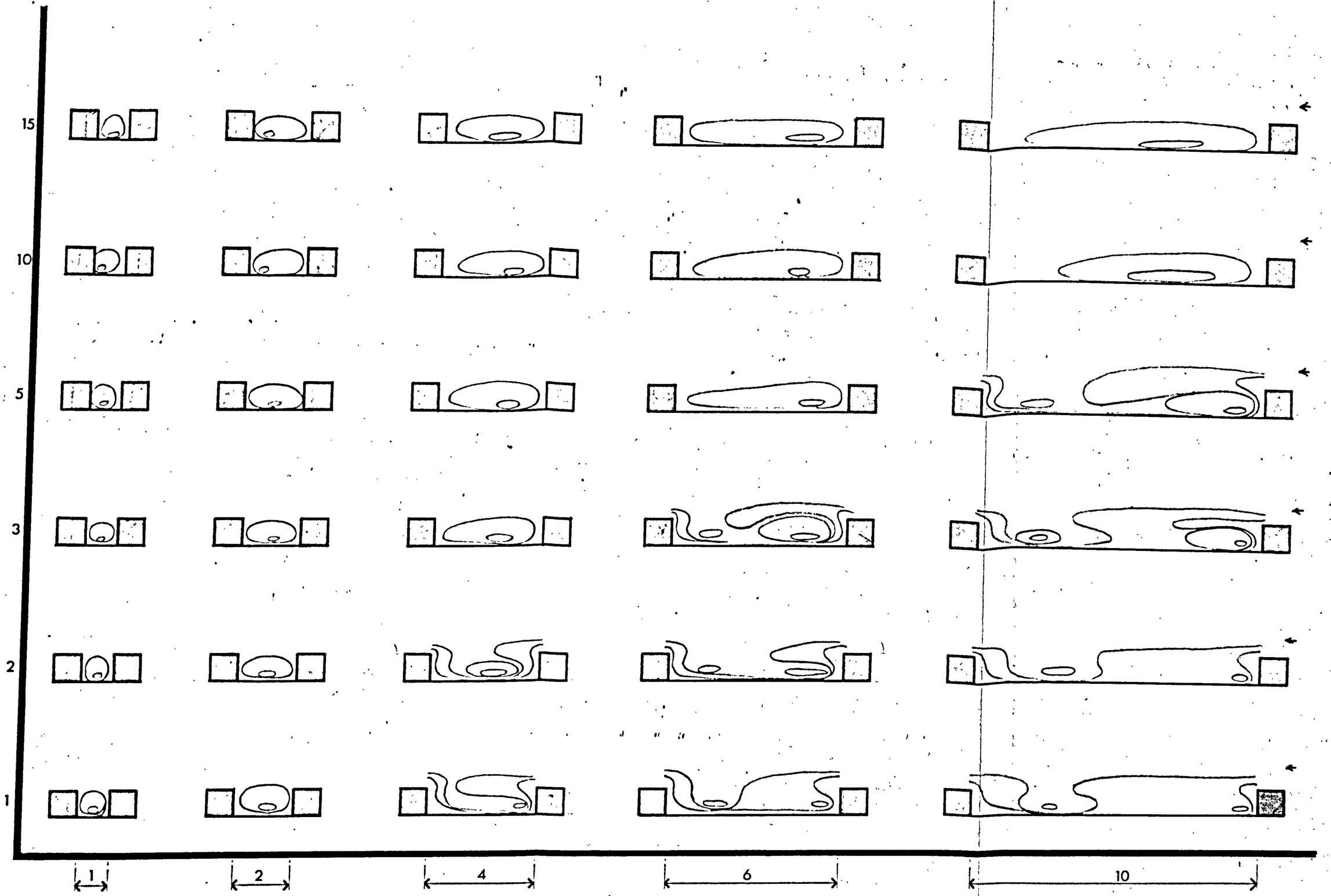
3.06 In diagrams 3.5 - 3.54 flow patterns are constructed for each of the orientations of couples of parallel blocks with 20 lengths and 10 space sizes. Diagrams 3.5 - 3.24 represent speed contours where flow axis is normal to the block length ($\theta = 0°$). Diagrams 3.25 - 3.39 show speed contours at orientations where the flow axis is oblique at 30° to

MORPHOLOGICAL SUMMARY OF FLOW PATTERNS '1'

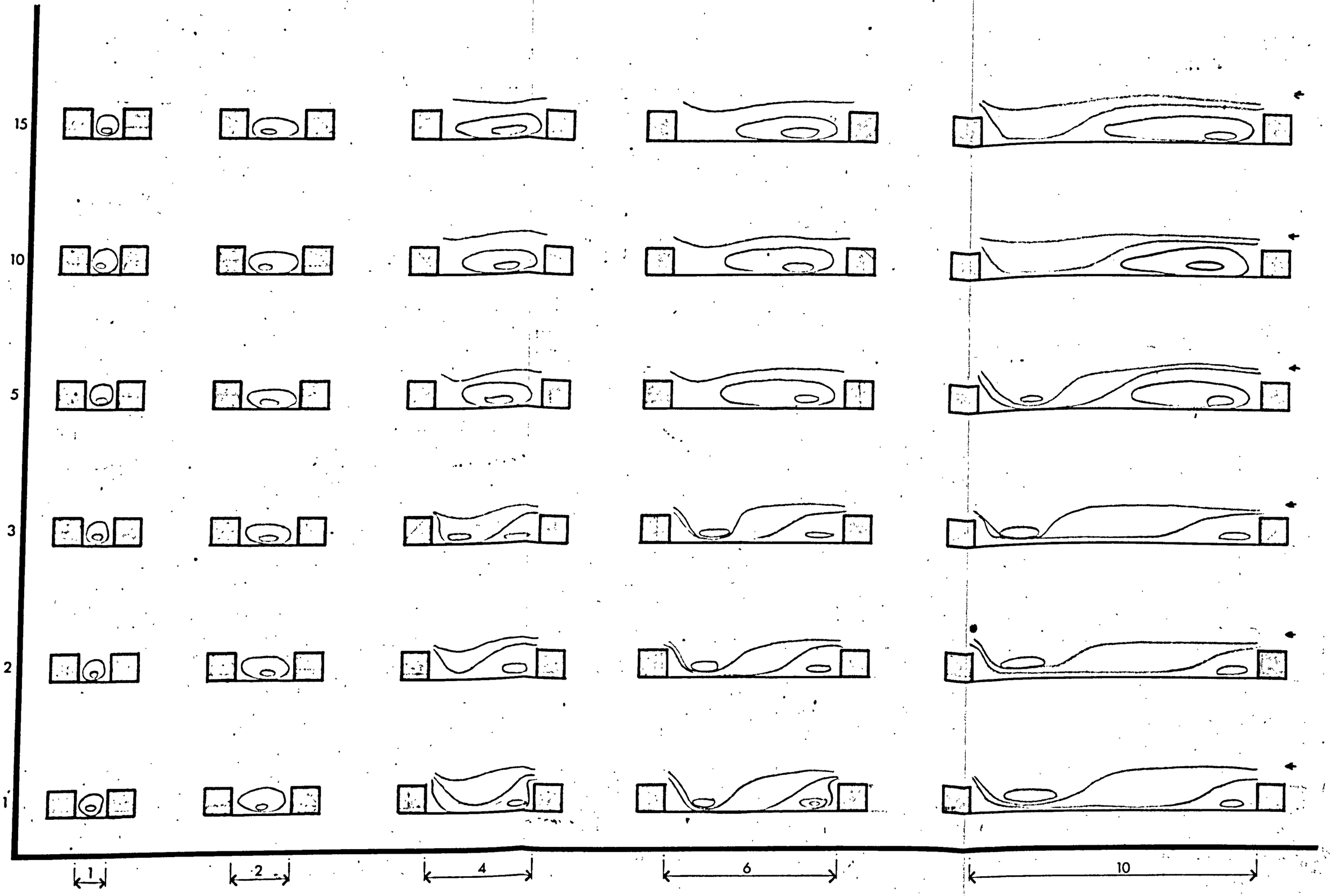
	Characteristic of short block lengths at small spacings and long block lengths at all spacings at orientation 0°. Also characteristic of small spacings and shorter block lengths at oblique orientations to flow.
	Characteristic of large spacings of long block lengths at oblique orientations to flow.
	Characteristic of small block lengths at large spacings with 0° orientations.
	Characteristic of small block lengths at large spacings and medium oblique orientations.
	Characteristic of medium and shorter block lengths with medium spacings and medium or large obliqueness.
	Characteristic of medium spaced short block lengths slightly oblique to flow.
	Characteristic of small block lengths at large spacings slightly oblique.

KEY

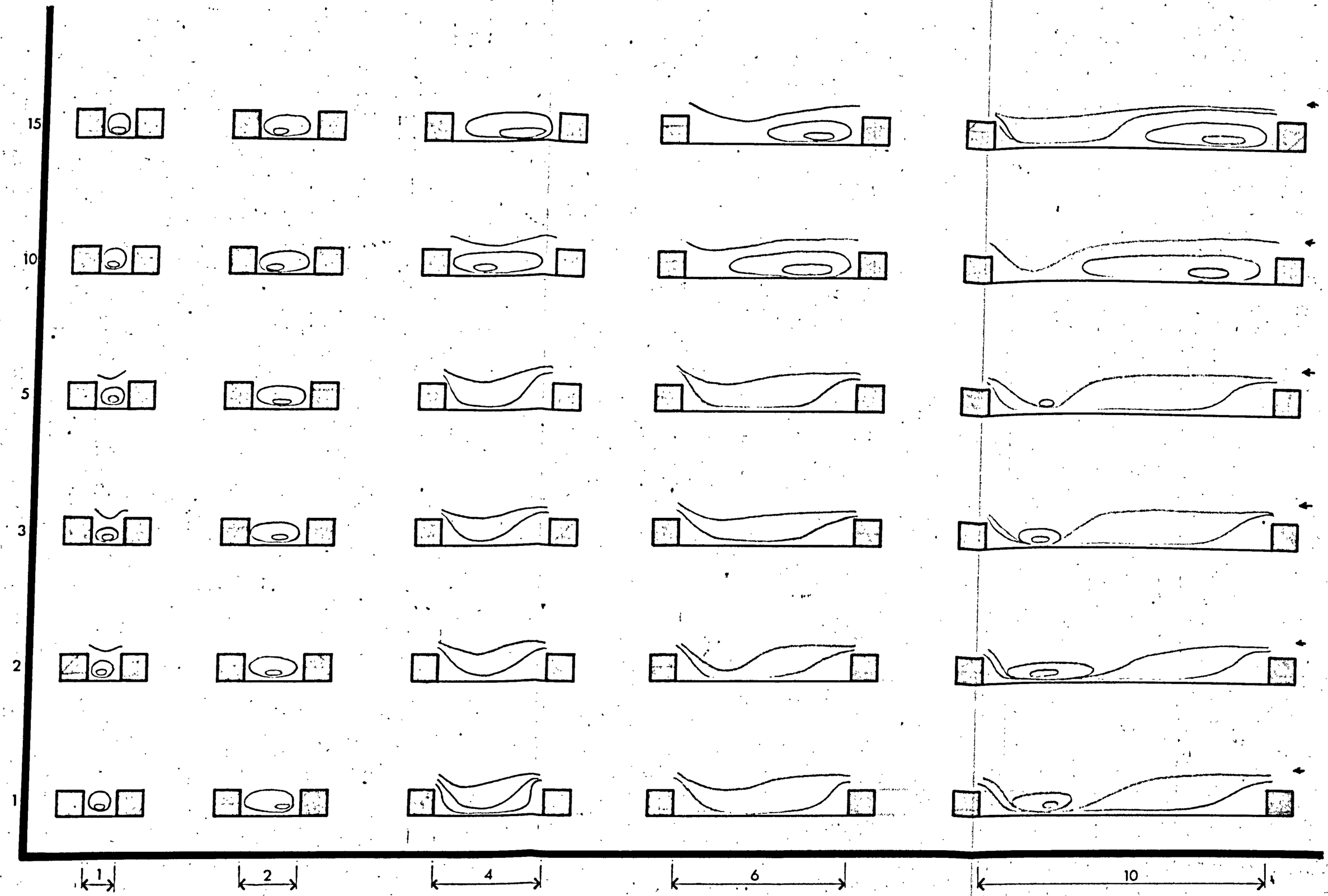
	Higher speed regions (vortices).
	Medium speed regions of main flow body. Lowest speed regions abut on the blocks and ground.



MORPHOLOGICAL SUMMARY 2 ($\theta = 0^{\circ}$)



MORPHOLOGICAL SUMMARY 2 ($\Theta = 30^{\circ}$)



MORPHOLOGICAL SUMMARY 2 ($\Theta = 45^{\circ}$)

the measurements plane ($\theta = 30°$) and diagrams 3.40 - 3.54 represent speed contours at $\theta = 45°$. Each diagram contains 10 space sizes for a single block length. The numbers under each figure indicate the block length and the space size. Thus, 1.05 indicates that the block length is 1 unit and the space size is 5 units. Comments on the pattern of flow for each block length at all orientations accompany the diagrams, showing the characteristics of the patterns and the main developments as the form aspects change.

GENERAL DISCUSSION OF THE RESULTS

4.01 The changes in the form aspects have profound effects on the patterns and the spatial distribution of the speeds within the measurement plane. The normal orientation ($\theta = 0°$) shows single and double vortices (closed speed contours; otherwise known as bubbles) at certain space sizes, usually one vortex prevails filling the whole space. As the block length: length increases the only observable changes concern the speed values and the positions of highest speed regions. The highest speed values tend to increase with the increase in block length until about block lengths 10 - 12 and then they begin to decrease. The positions of the highest speed regions shift between the downwind, central and upwind positions within the space; but they always occur at the lower levels. In general, at small space sizes, they locate centrally within the space, but they move towards the downwind end of the space as the block length increases. There are, however, some deviations from this pattern showing a location of highest speed regions centrally and towards the upwind end at spaces 1 and/or 2 for longer block lengths.

4.02 The increase in space size at this orientation causes a break in

the space-filling vortex to form two vortices. The two vortices prevail only for shorter block lengths and are located at the upwind and downwind ends of the space. As the block length increases, the occurrence of the downwind vortex becomes limited to larger space sizes with the intermediate space sizes containing single space-filling vortices. At block length 6, the downwind vortex persists only at space size 10 and at block length 7 it disappears completely. Further increases in block length show an upwind vortex at spaces 9 and 10. This vortex increases in size with increase in block length until it fills space 9 and reaches its maximum size for space 10 (5/6 of the space) at block length 11. From this block length on, the single space-filling vortex becomes characteristic of the flow patterns of all the spaces at this orientation.

4.03 When the orientation is oblique at $\theta = 30°$, the speed contours show a substantially different picture. Although the single space-filling vortex persists for small space sizes, the contours show a 'dip' towards the downwind end of the space in all arrangements. The dip, however, is more pronounced in some cases than in others. Sometimes, in shorter block lengths with intermediate or large spaces, the dip develops a downwind vortex in addition to the upwind one. In these cases, and as the flow passes the upwind block, the upwind vortex is below the spreading mainstream of the flow and the downwind vortex is above its narrowing descending band. The downwind vortex disappears at about block length 7, the same as in the case of the normal orientation. From that block length on the speed contours fall into two main groups: a space-filling vortex for the shorter spaces and a fairly large upwind vortex decreasing with increase in space size. The dip of the mainstream of the flow persists, but it becomes less pronounced.

4.04 At orientation 45° the most important development is the disappearance of the upwind vortex at shorter block lengths. Therefore, at this orientation arrangements show one or no vortex at all. The single space-filling vortex continues to exist at the small spaces throughout the range of block lengths. At shorter block lengths of larger space, downwind vortices prevail, but they become smaller, weaker and restricted to the largest one or two spaces as the block length increases from 1 to 5. At block length 6 there are two vortex types: the single space-filling vortex at small spaces, and a relatively large upwind vortex at large spaces 9 and 10. For the intermediate spaces, the speed contours are characterised by a dip towards the downwind end of the space where the highest speeds for these arrangements occur. As the block length increases, the appearance of the upwind vortex comes earlier, until block length 8 where all space sizes show vortices. These are mostly single upwind vortices at space sizes 5 - 10 and single space-filling vortices at spaces 1 - 4. The patterns remain more or less the same as the block length increases; the only changes are slight increases in the sizes of the larger spaces vortices and in the values of their highest speeds.

CONCLUSIONS

The quantitative visual representation of flow is important to the designer in discerning the numerical and spatial variations in the flow patterns. Flow visualisation studies have so far used media which, notwithstanding their time-saving advantages, offer no quantitative information about flow patterns. In this chapter, the problems and descriptive properties of a quantitative visual description of flow have been demonstrated for some simple model arrangements. The advantages of the

method lie in presenting the designer with a set of pictorial and numerical information against a controlled change of desirable form aspects. In cases where the progressive change in form aspects shows no substantial change in patterns, as conventional flow visualisation media would also show, the method has the further advantage of detecting the quantitative changes in the patterns (values of speed contours, changes in highest and lowest speed values, etc.) which remain pictorially unchanged. For a designer, this provides a handy yardstick in studying and selecting appropriate forms for his design.

An example of relevant applications of such information can be urban landscape design, where the location of such elements as plants, seats, and walkways can be very much influenced by the patterns of wind speeds in the relevant space.

The main disadvantage of the method lies in its time-consuming technique created by the need for detailed grid measurements of velocities. This disadvantage is most appreciated in this study since it was undertaken using a single probe which had to be manually operated. For a large scale project comprising a wider array of variations in form, it would be expedient to be able to use a number of probes.

Another problem in the development of quantitative flow patterns is the presentation problem. For the progressively changing forms in this investigation it was necessary to present each arrangement, for the greatest part, individually. There is no simple way of overcoming this, except, as in this case, when the progression of forms allows for broad categorisation. Such categorisation is the basis of a 'morphological summary' of flow patterns. The summary, however, is no substitute for the individual linked study of change in flow patterns. This has to be done, if the investigation is to be meaningful in a design context, to arrive at better guided design decisions. The role of the morphological summary remains to give

general initial guidance about what to expect before intensive research is launched.

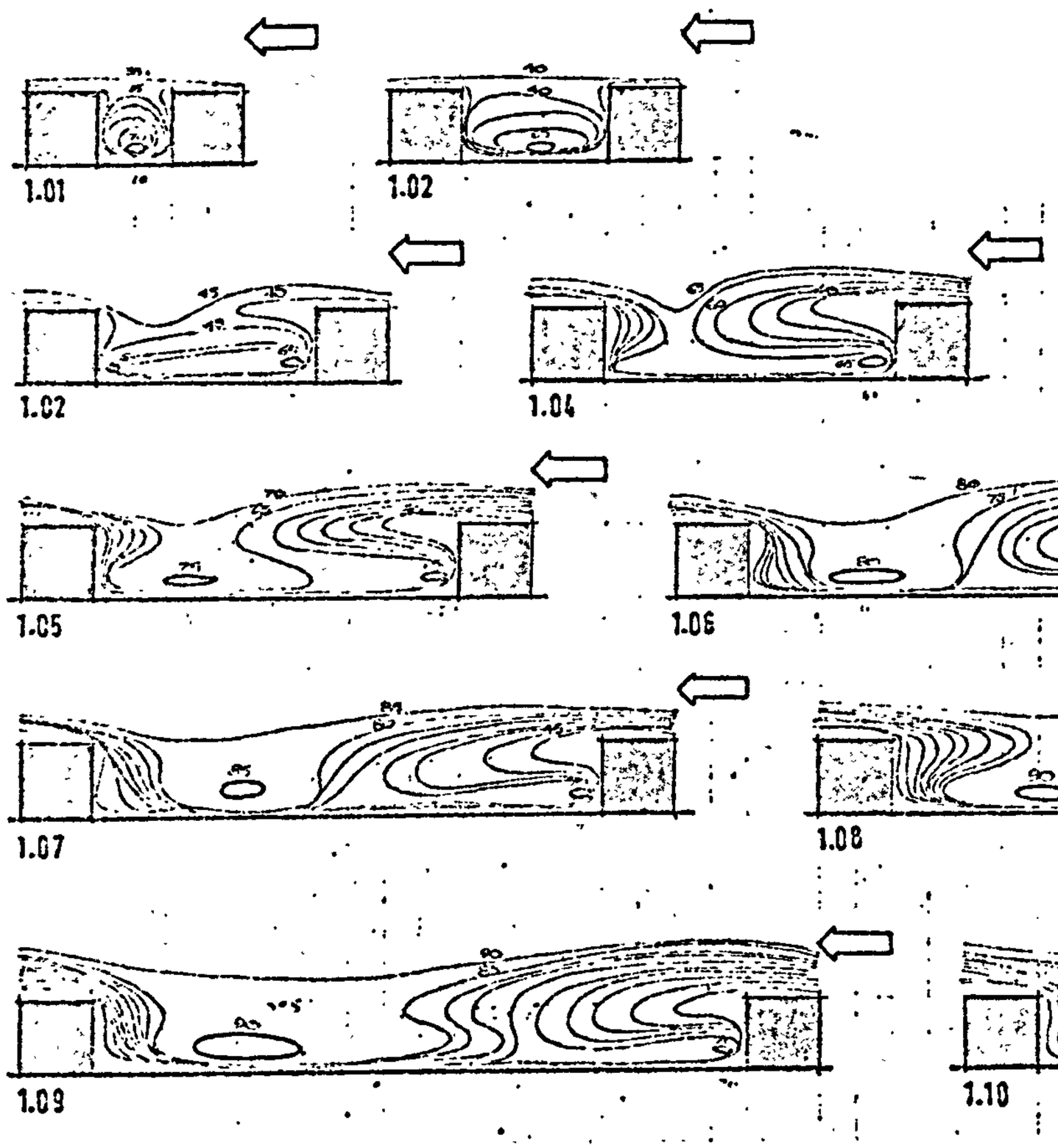
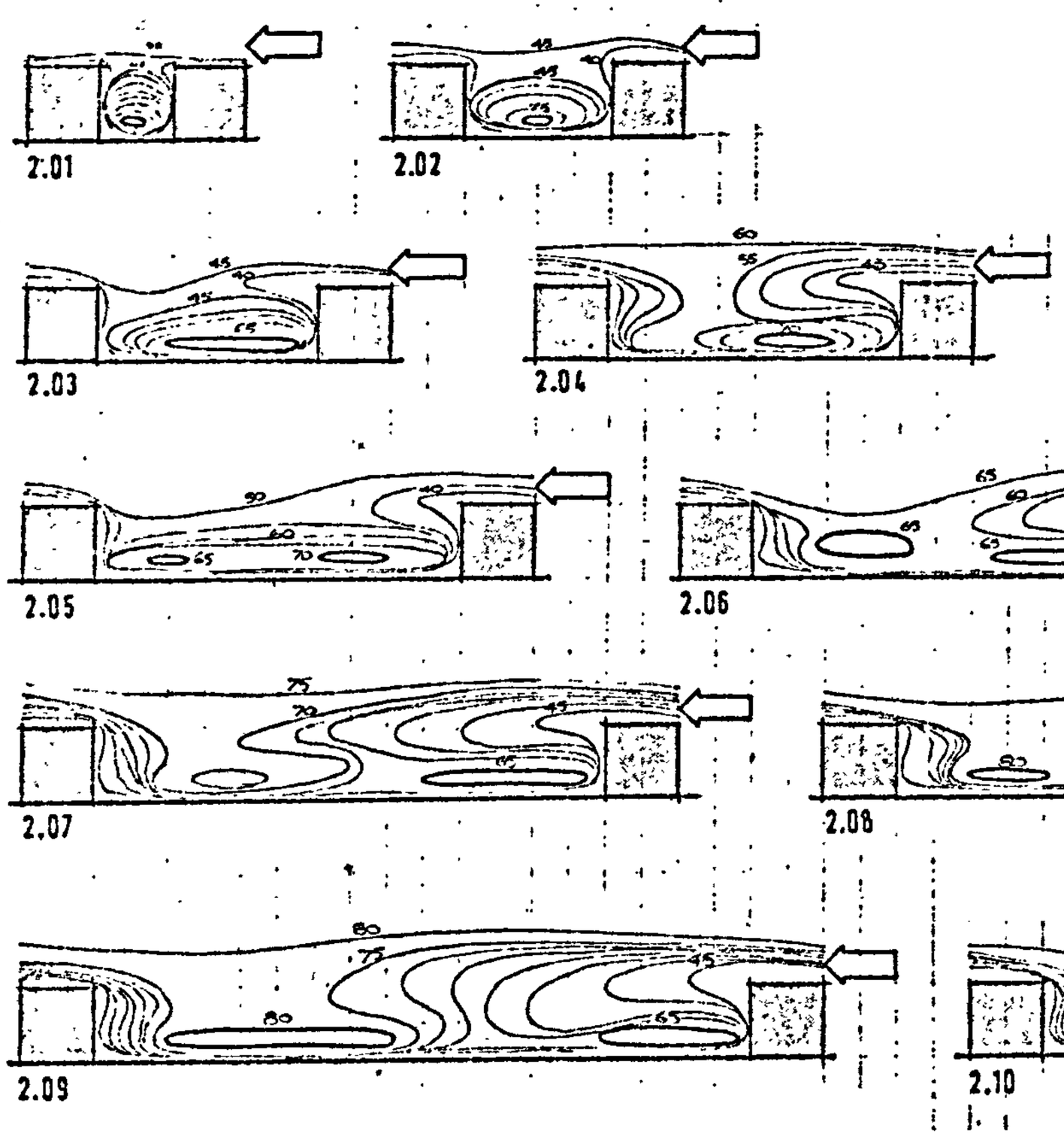


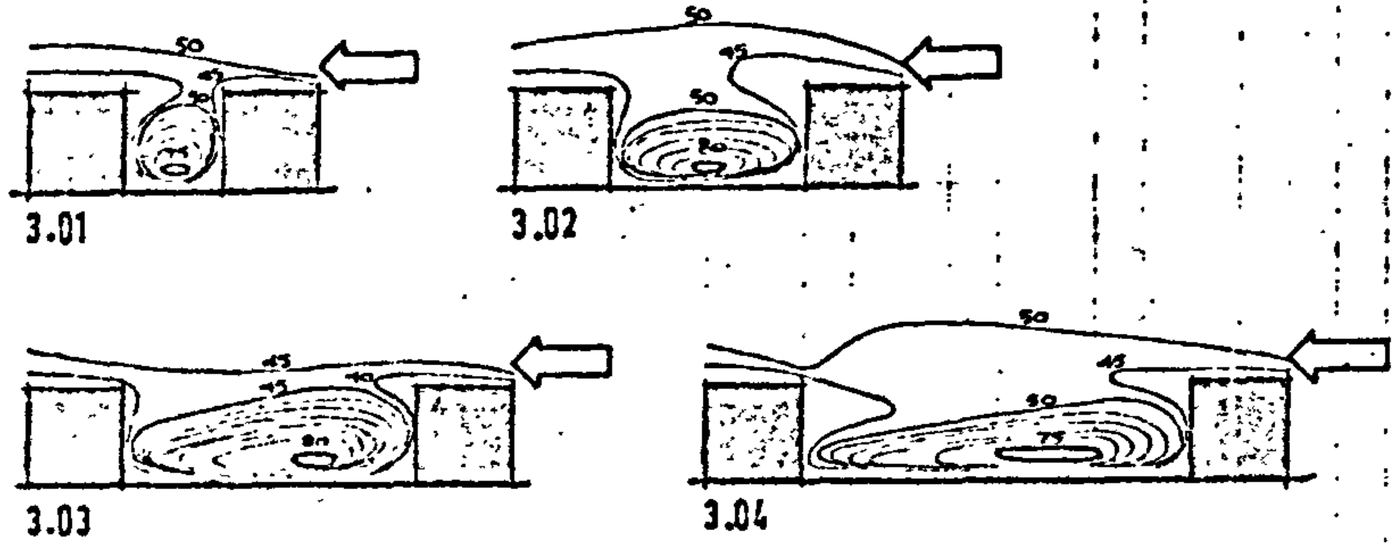
DIAGRAM 3.5: FLOW PATTERNS AT BLOCK LENGTH 1. ($\theta=0^{\circ}$)

This is the smallest unit in the range of block lengths investigated for flow patterns. Vortices appear at smaller space sizes filling the whole space. As the space increases two vortices appear near to the blocks. They are characterized with high velocity but small in size, in relation to those at smaller space sizes. The highest velocities occur at low levels and the centre of the space for small space sizes. For larger space sizes the position of highest velocity shifts to be nearer to the downwind block. Highest velocity values increase with spacing.



At this block length the vortices persist at smaller space sizes with values of highest velocity slightly more than in the previous case. For larger spacings the vortices become larger but weaker than previously. The emergence of two vortices is delayed until space size 5. After an initial drop, highest velocity values increase with increase in spacing. The position of highest velocities shifts from the centre of the space at small space sizes towards the downwind block at larger space sizes.

DIAGRAM 3.6: FLOW PATTERNS AT BLOCK LENGTH 2 ($\theta = 0°$)



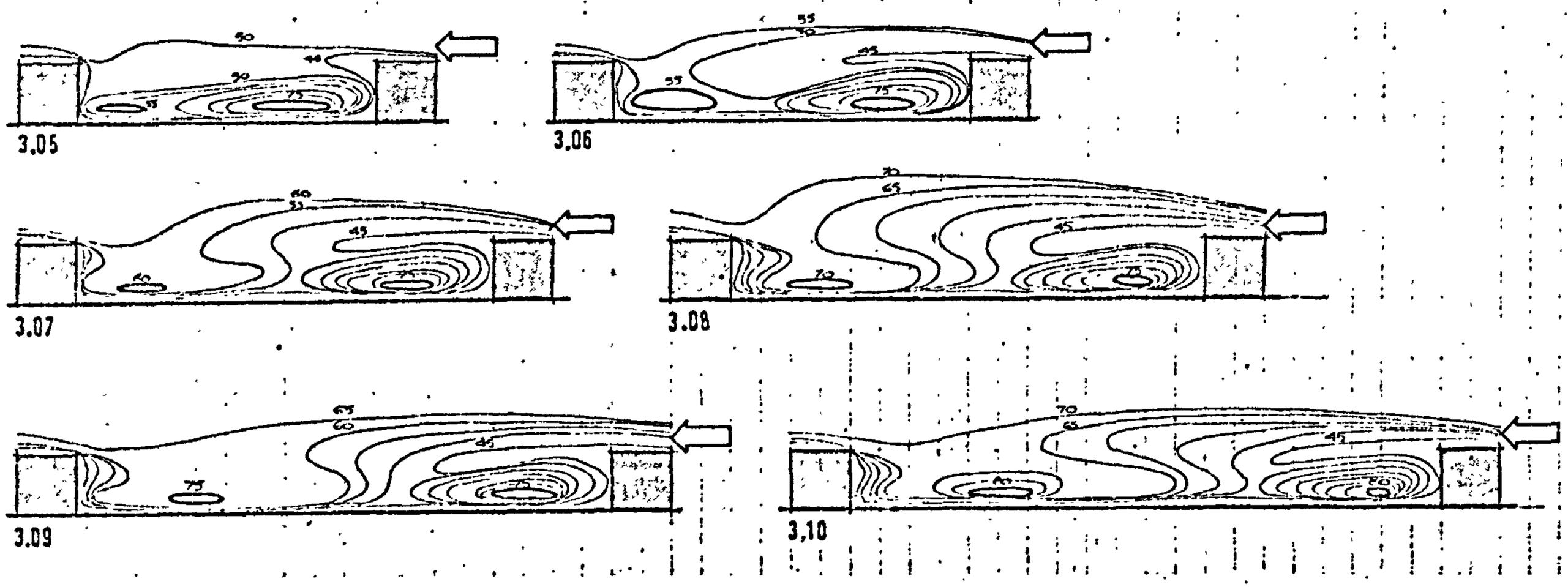
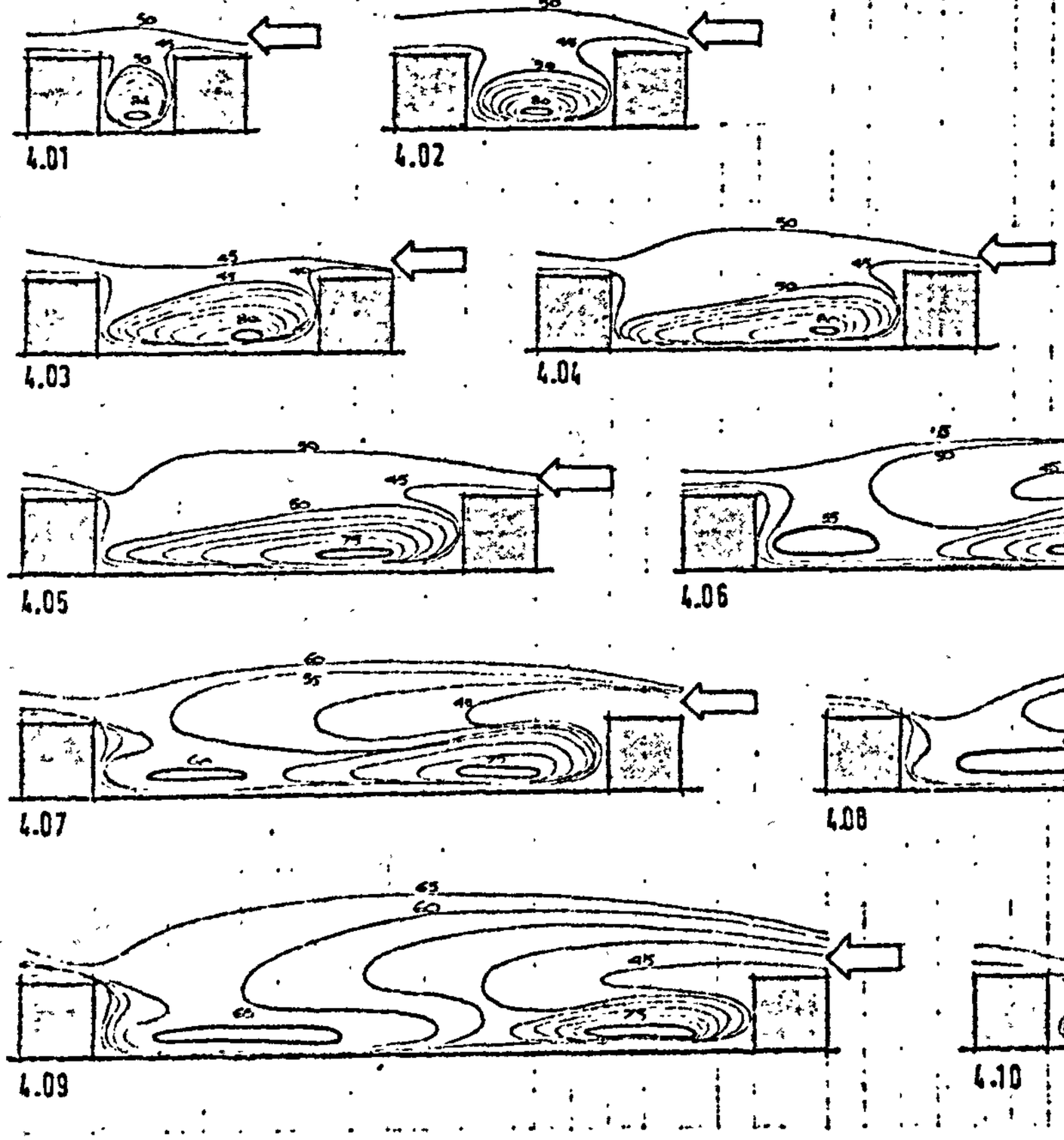


DIAGRAM 3.7: FLOW PATTERNS AT BLOCK LENGTH 3 ($\theta = 0°$)

The increase of block length in this case creates a mature vortex filling the whole space and expanding horizontally as the space increases from 1 to 5. At space 6 two vortices appear; one upwind and the other downwind. The upwind vortex is larger and can be regarded as inherited from the previous space size. The downwind vortex is smaller and weaker but increases in highest velocity with increase in space until it equalizes the highest velocity value of the upwind vortex at spacings 9 and 10.



Flow patterns are basically similar to the previous case but there are some differences. The upwind vortex in the larger spacings is slightly smaller and the downwind is slightly larger than in the previous case. Where there are two vortices the upwind is always the stronger and larger. The maximum highest velocities occur at the smaller spacings and at spacing 10, the largest space size with the intermediate spacings having a relatively lower highest velocity values.

DIAGRAM 3.8: FLOW PATTERNS AT BLOCK LENGTH 4 ($\theta = 0°$)

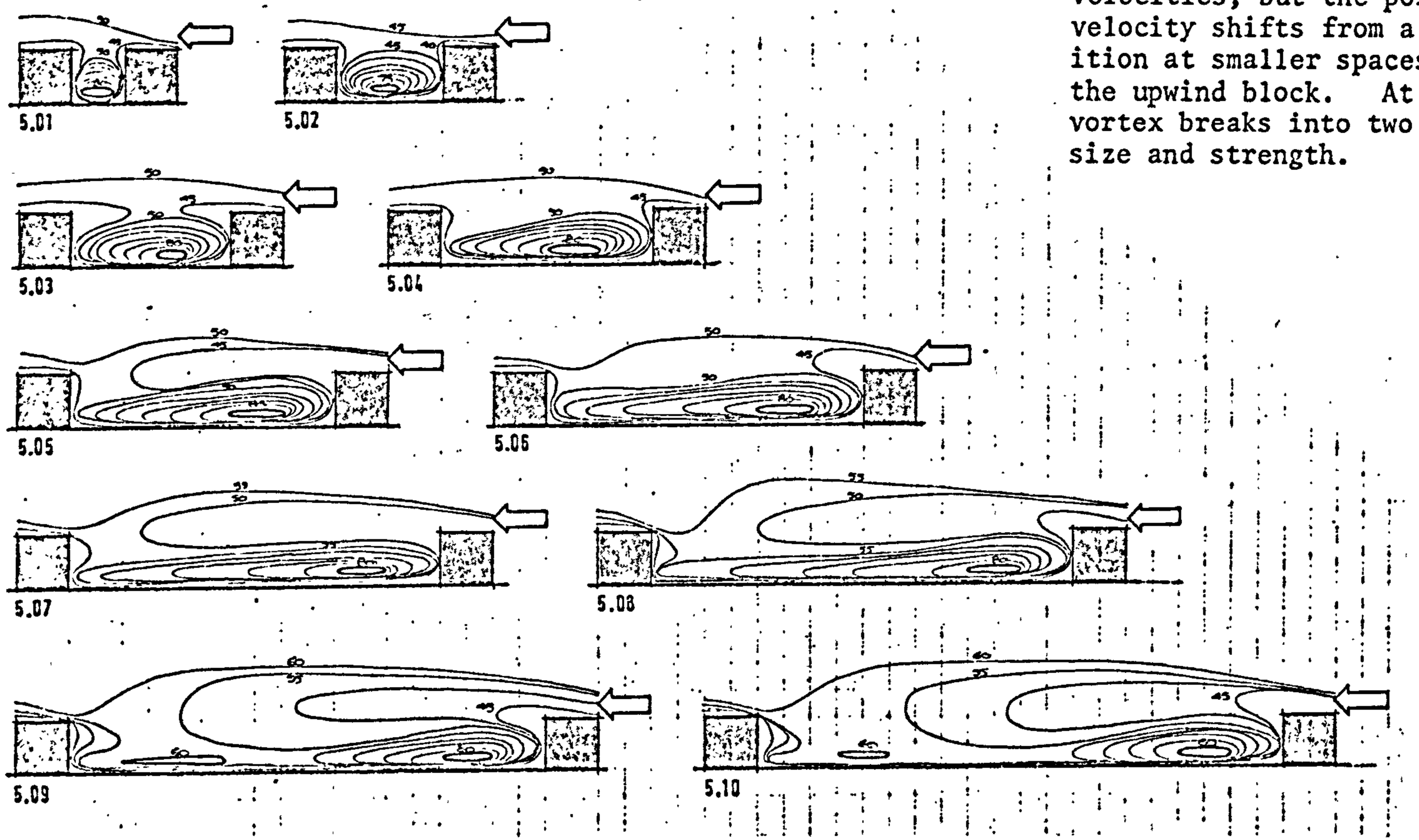


DIAGRAM 3.9: FLOW PATTERNS AT BLOCK LENGTH 5. ($\theta = 0°$)

This block length marks the beginning of a longer persistence of the single vortex as the space increases. With the increase in the space size from 1 to 8 the vortex expands horizontally to fill the space. There is no significant change in the values of highest velocities, but the position of the highest velocity shifts from a relatively central position at smaller spaces to a position near the upwind block. At spacings 9 and 10 the vortex breaks into two vortices unequal in size and strength.

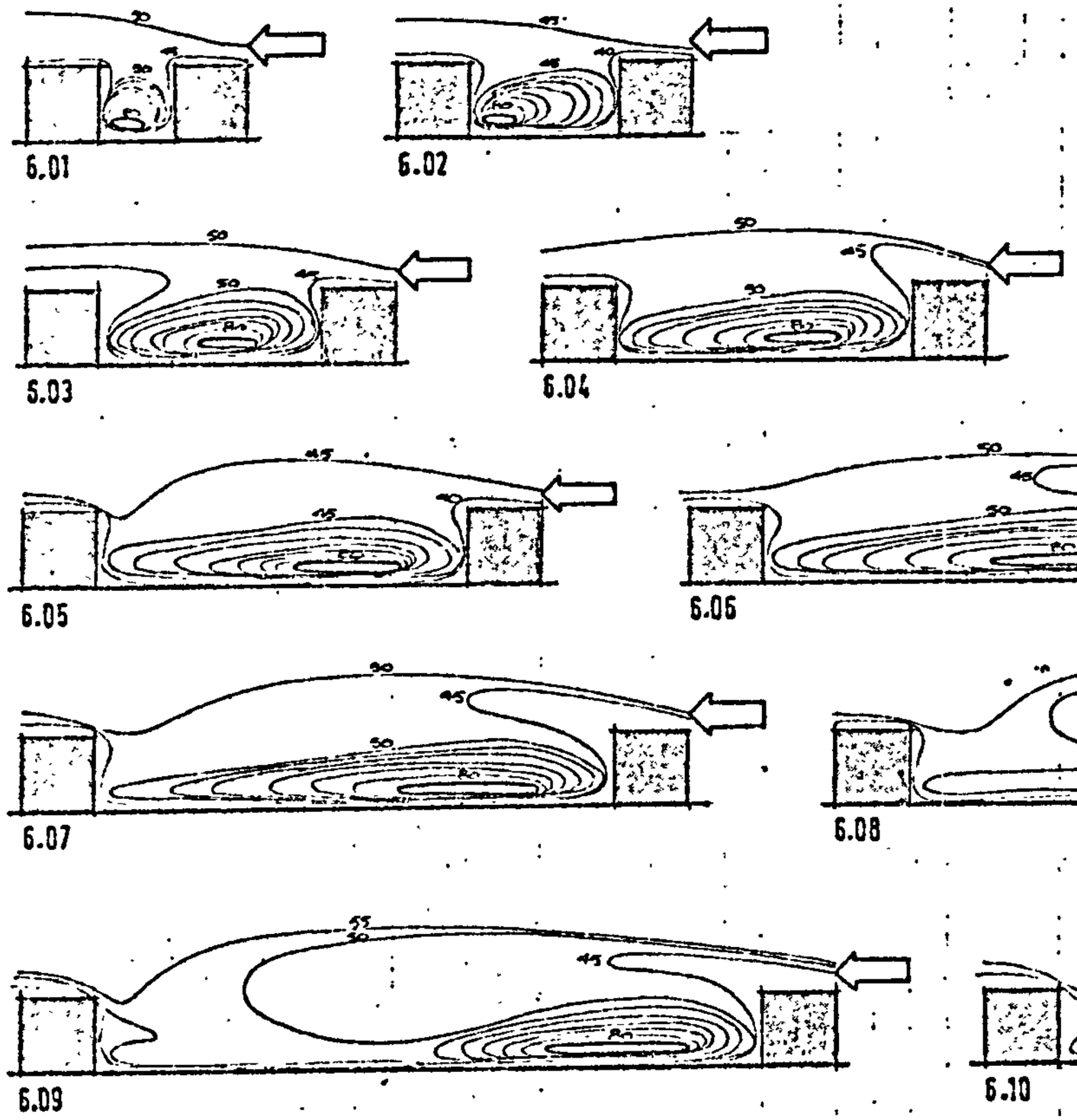
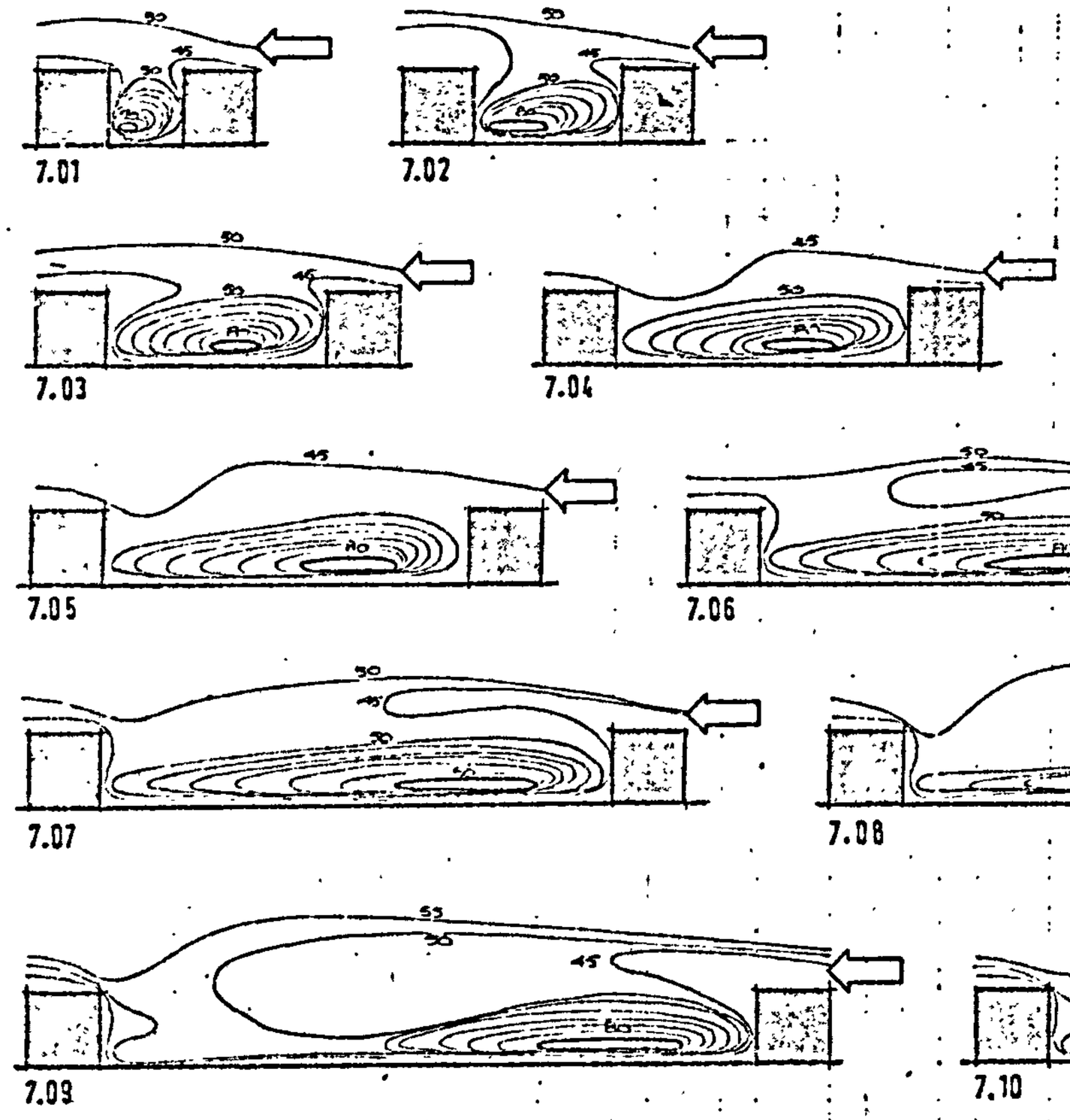


DIAGRAM 3.10: FLOW PATTERNS AT BLOCK LENGTH 6 ($\theta = 0°$)

This arrangement shows some differences from the previous one. The position of the highest velocity at spaces 1 and 2 are closer to the downwind block. The regions of highest velocity values are slightly larger than before. The appearance of a downwind vortex comes at space size 10. Space size 9 has only a small vortex at the upwind side which is an intermediate pattern between the space filling vortex of the spaces 1 to 8 and the two-vortex patterns of space 10. Highest velocities remain the same throughout the space changes.



This arrangement is characterized by the absence of the two-vortex pattern. The vortex expands horizontally with the increase in space size between 1 and 8. At spaces 9 and 10 the vortex shrinks to occupy less than half the space at the upwind end. The maximum highest velocity 90%, occurs at the smallest space, 1. For the remaining space sizes the highest velocities are 80% except at space 10 where the highest velocity is 85%. Similar to the previous case the highest velocity zone occurs at the downwind end at spaces 1 and 2 but shifts to a position near the upwind end with increase in space size.

DIAGRAM 3.11: FLOW PATTERNS AT BLOCK LENGTH 7 ($\theta = 0°$)

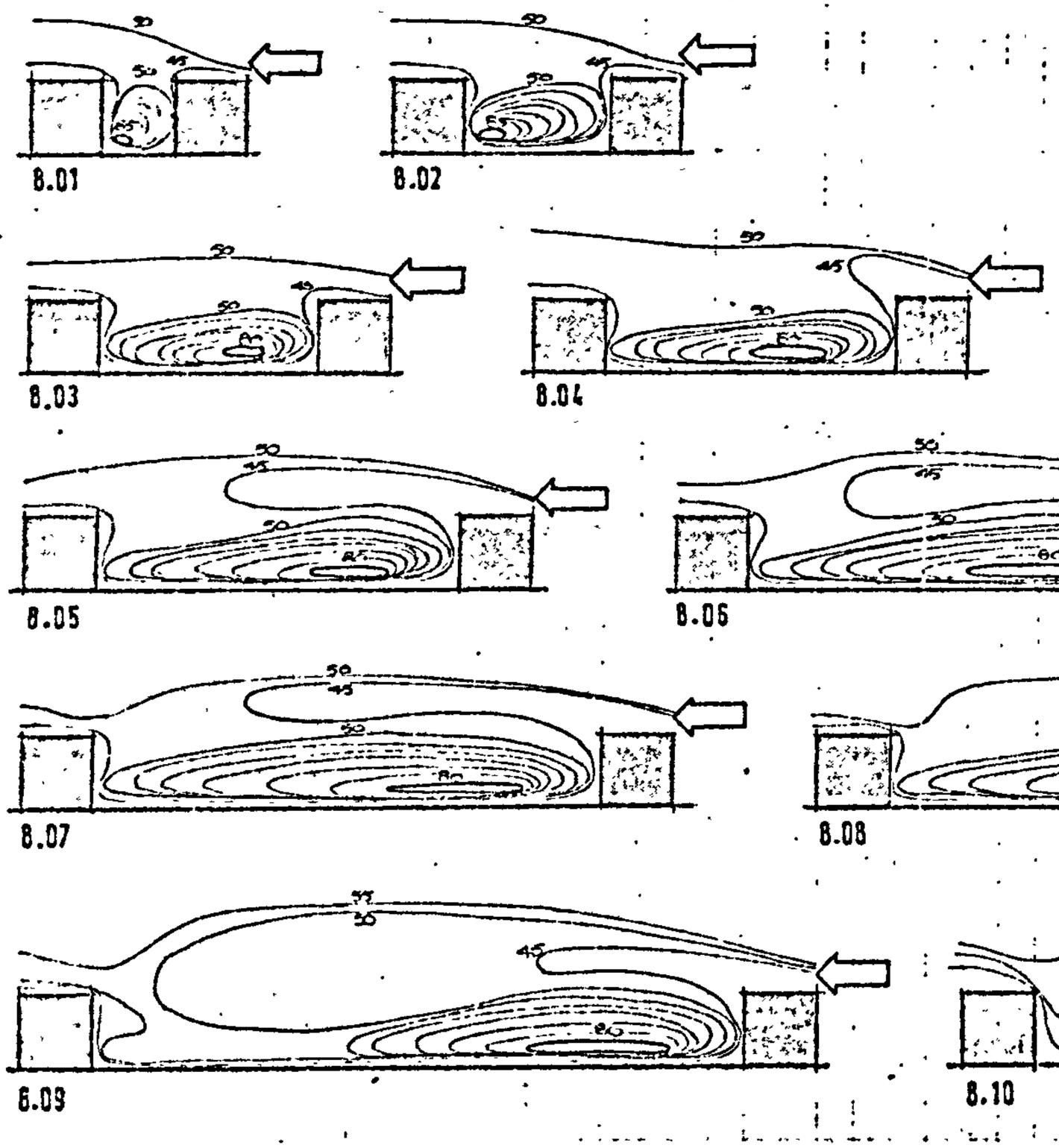


DIAGRAM 3.12: FLOW PATTERNS AT BLOCK LENGTH 8 ($\theta = 0°$)

The patterns of flow in this case are basically similar to the previous case with only slight differences. The maximum highest velocity values occur at the space size extremes: 1,2 and 10 and is of value 85%. Again the position of highest velocity shifts from the down-wind end to the upwind end as the space increases. The sizes of the vortices at spacings 9 and 10 are slightly larger than in the previous case.

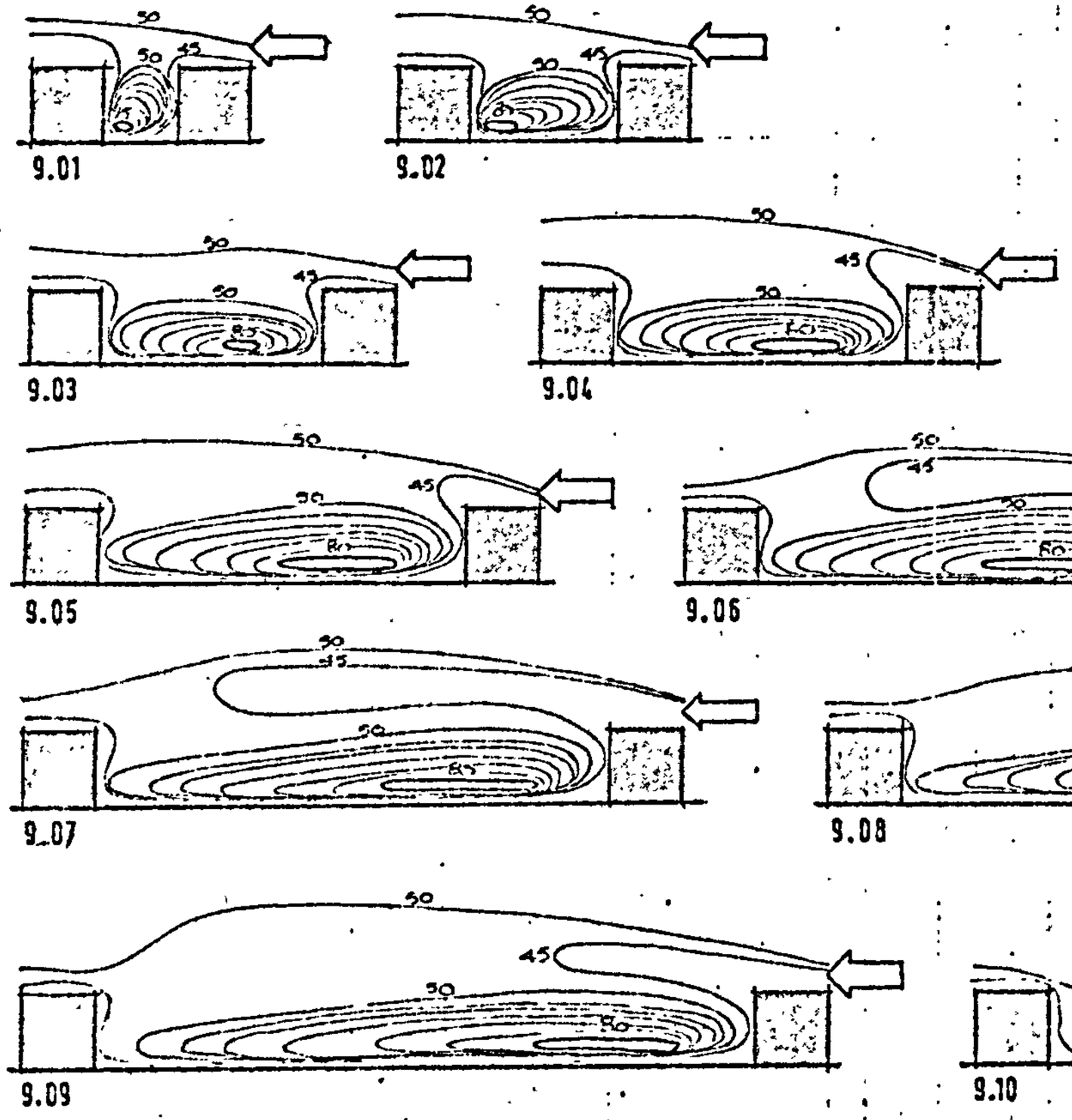


DIAGRAM 3.13: FLOW PATTERNS AT BLOCK LENGTH 9 ($\theta = 0°$)

At this block length the patterns are such that the vortex expands horizontally as the space increases from 1 to 9. At space 10 the vortex fills only about 2/3 of the space and is larger than in the previous corresponding space size. The shift pattern of the position of the highest velocity zone is the same as before but the maximum highest velocity, 95%, occurs at spacing 1, dropping to 85%, 80% and increasing again to 85% at spacings 8, 9 and 10.

In this arrangement there are no significant changes from the previous pattern except that the vortex at space 10 is slightly larger. The highest velocities at spaces 8, 9 and 10 are less than the corresponding spaces in the previous case.

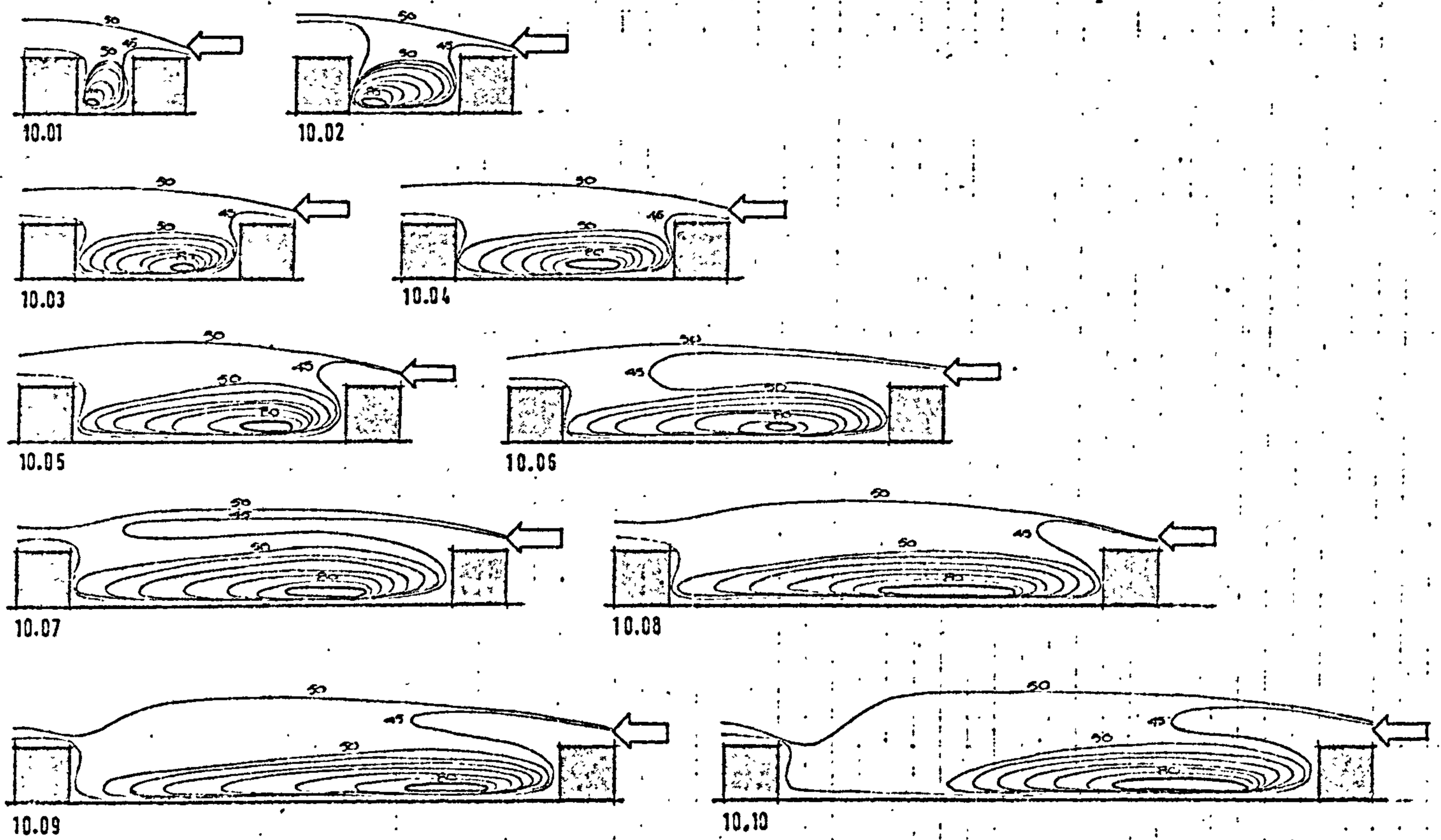
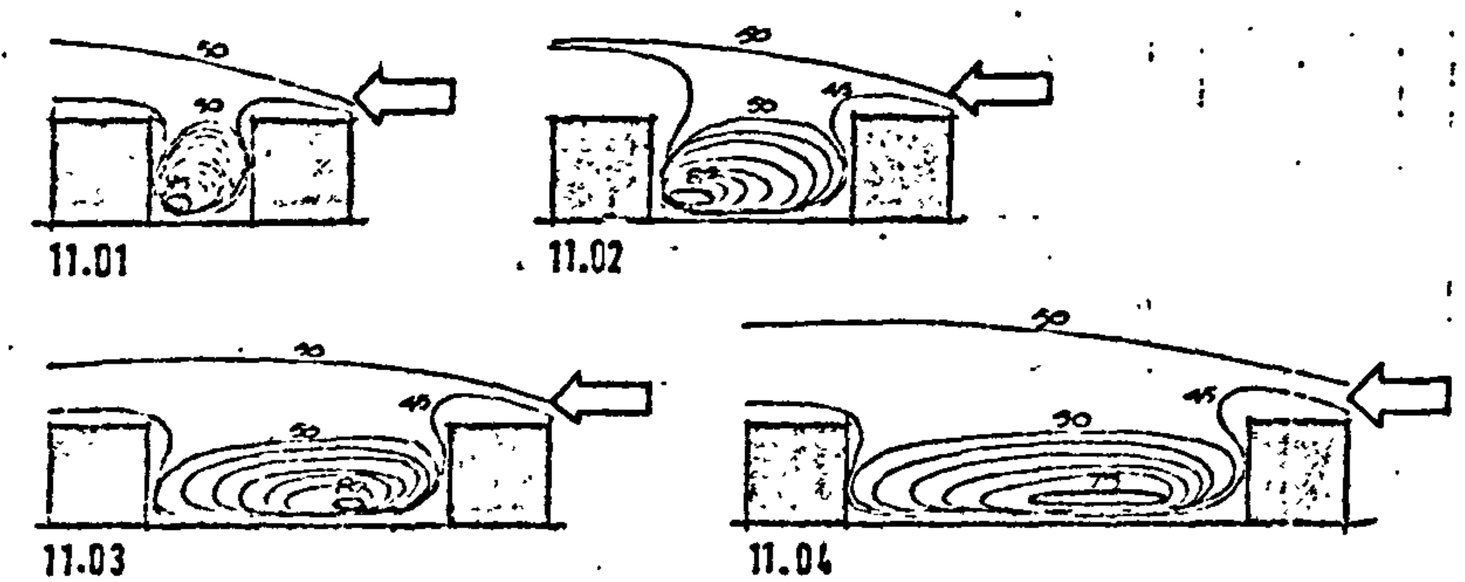


DIAGRAM 3.14: FLOW PATTERNS AT BLOCK LENGTH 10 ($\theta = 0°$)



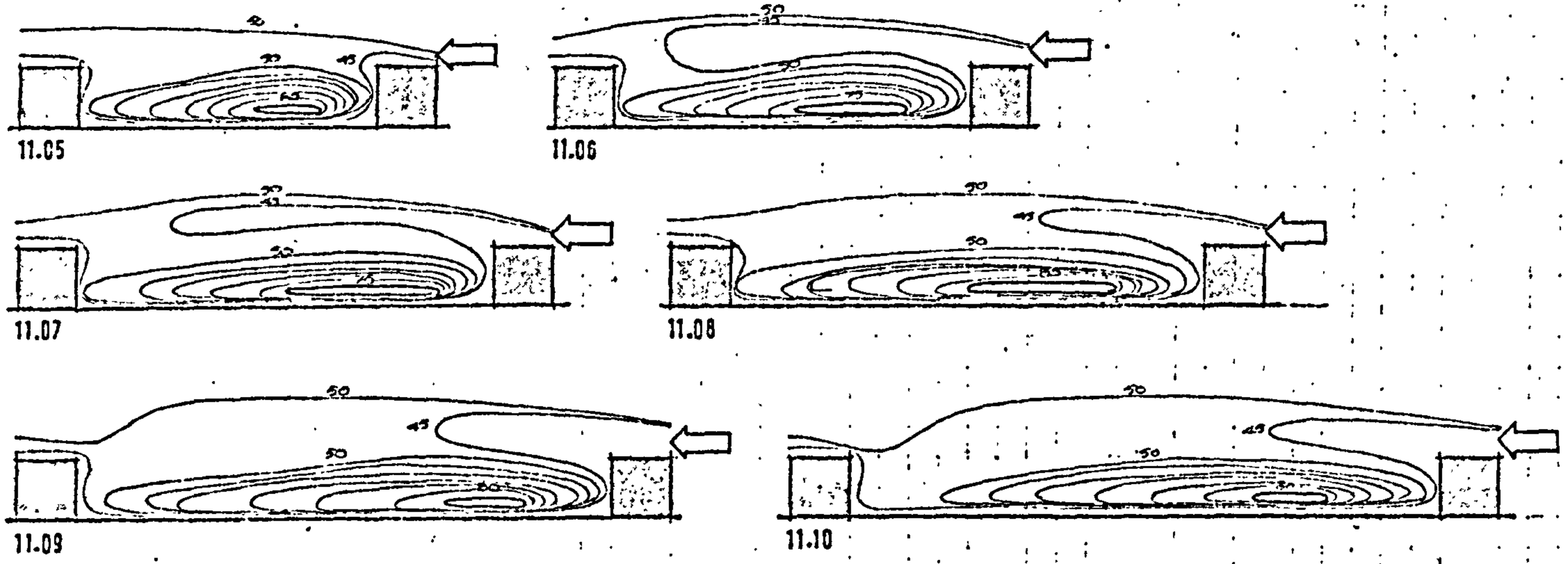


DIAGRAM 3.15: FLOW PATTERNS AT BLOCK LENGTH 11 ($\theta = 0°$)

At this block length the vortex expands horizontally as the space increases to fill the space although it falls slightly shorter at space 10. The maximum highest velocity occurs at space 1 but falls steadily with the increase in space size to 7. At space 8 it rises 80% and remains at this value for spaces 9 and 10.

The flow patterns in this case are similar to the previous one. At this arrangement a slight change in the position of the highest velocity regions begins to show. For larger spaces this moves slightly away from the upwind block - an effect which becomes more pronounced as the block length increases (see later). The value of the maximum highest velocity, 90%, occuring at space size 1, is less than the previous corresponding value.

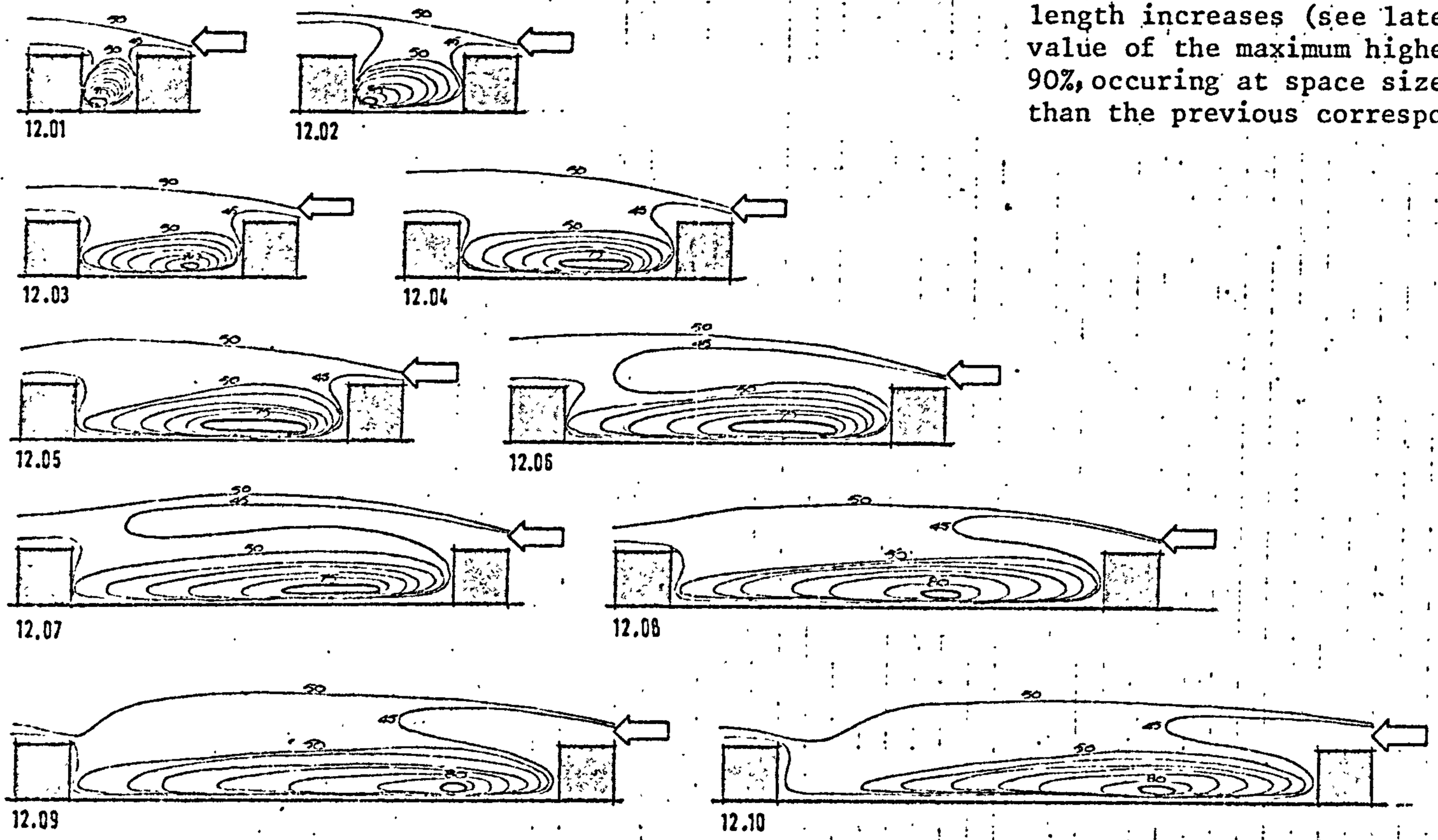


DIAGRAM 3.16: FLOW PATTERNS AT BLOCK LENGTH 12 ($\theta = 0°$)

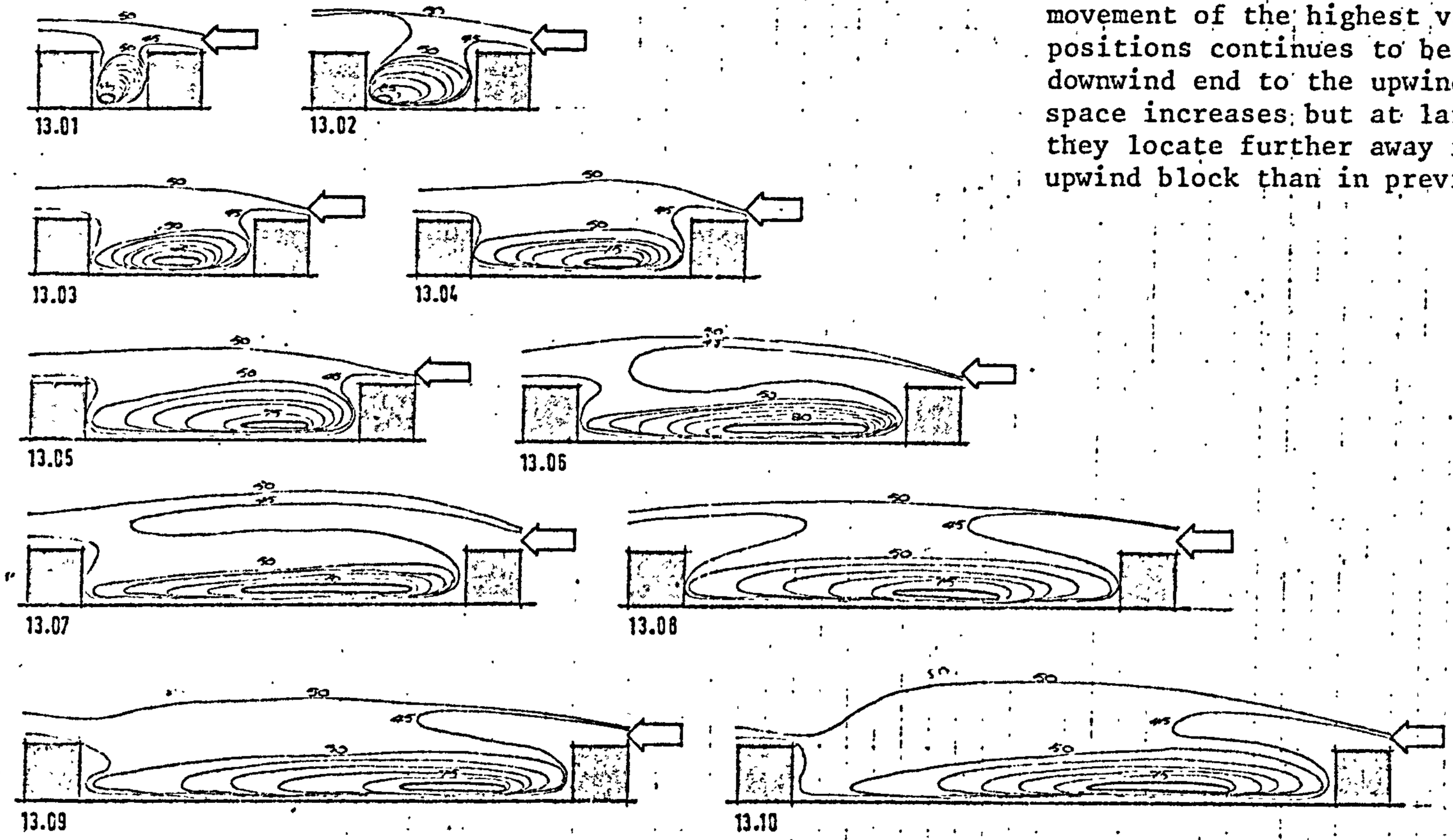


DIAGRAM 3.17: FLOW PATTERNS AT BLOCK LENGTH 13 ($\theta = 0°$)

The vortex continues to expand with the increase in space. The main change in this arrangement is the drop in the values of the highest velocities at spaces 8, 9 and 10. Although the overall pattern of movement of the highest velocity positions continues to be from the downwind end to the upwind end as the space increases, but at larger spaces they locate further away from the upwind block than in previous cases.

Apart from the drop in the value of the maximum highest velocity to 85% at space 1 the arrangements here show no significant change from the previous case.

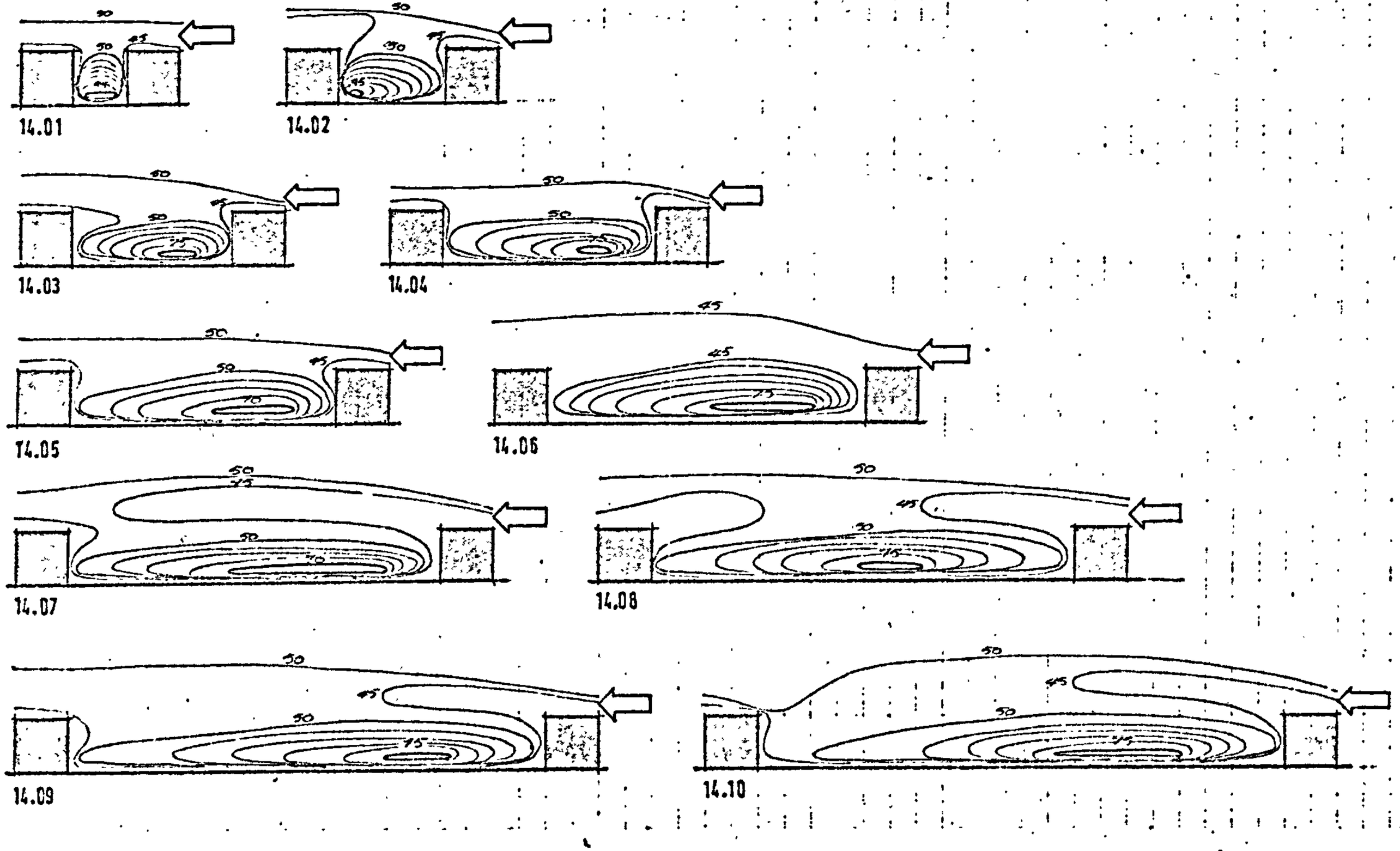


DIAGRAM 3.18: FLOW PATTERNS AT BLOCK LENGTH 14 ($\theta = 0°$)

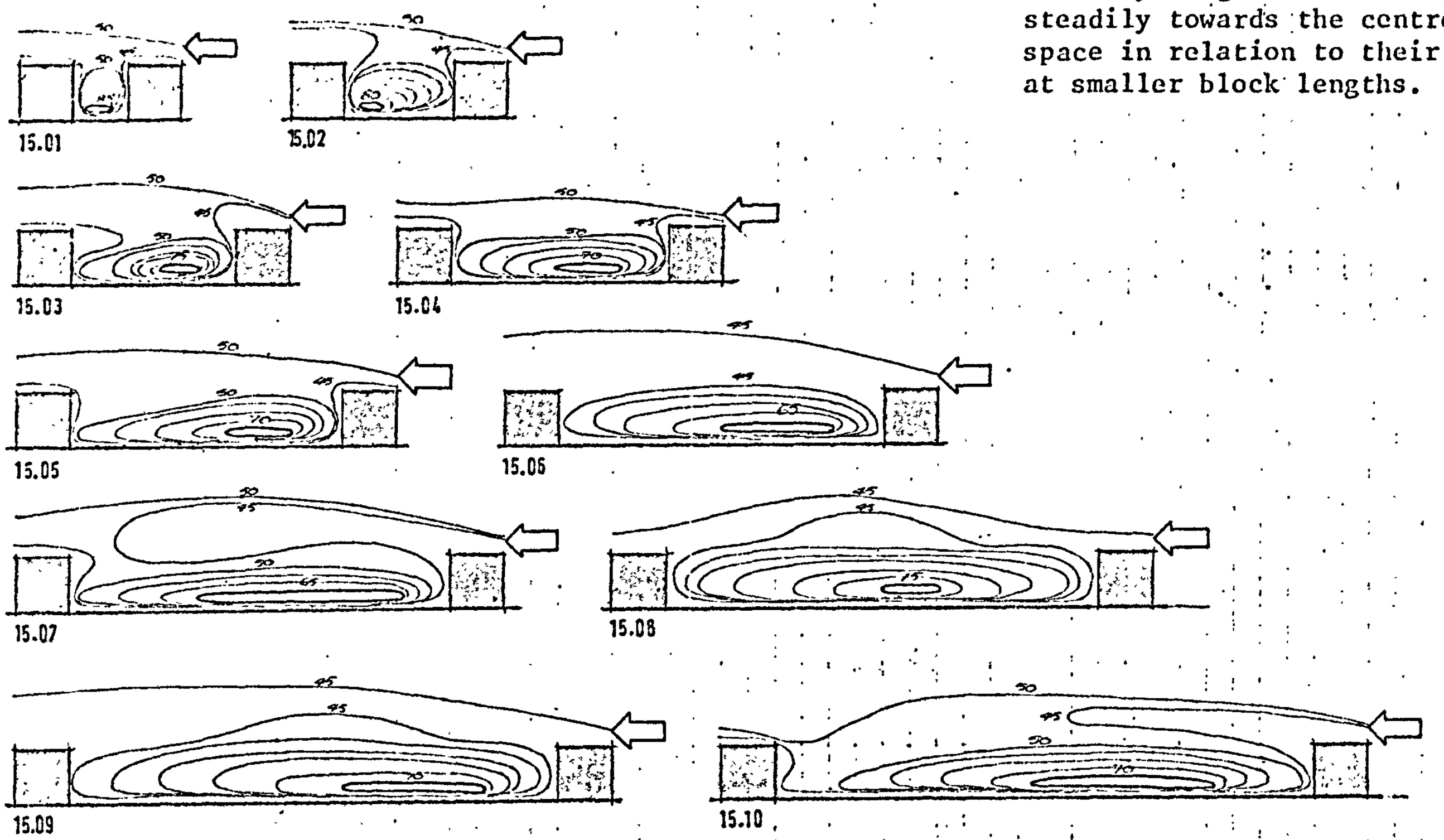


DIAGRAM 3.19: FLOW PATTERNS AT BLOCK LENGTH 15 ($\theta = 0°$)

In this case the main changes are the drop in the values of the highest velocities. In the larger spaces the highest velocity zones, with lower values than previously, occupy relatively larger areas and moving steadily towards the centre of the space in relation to their positions at smaller block lengths.

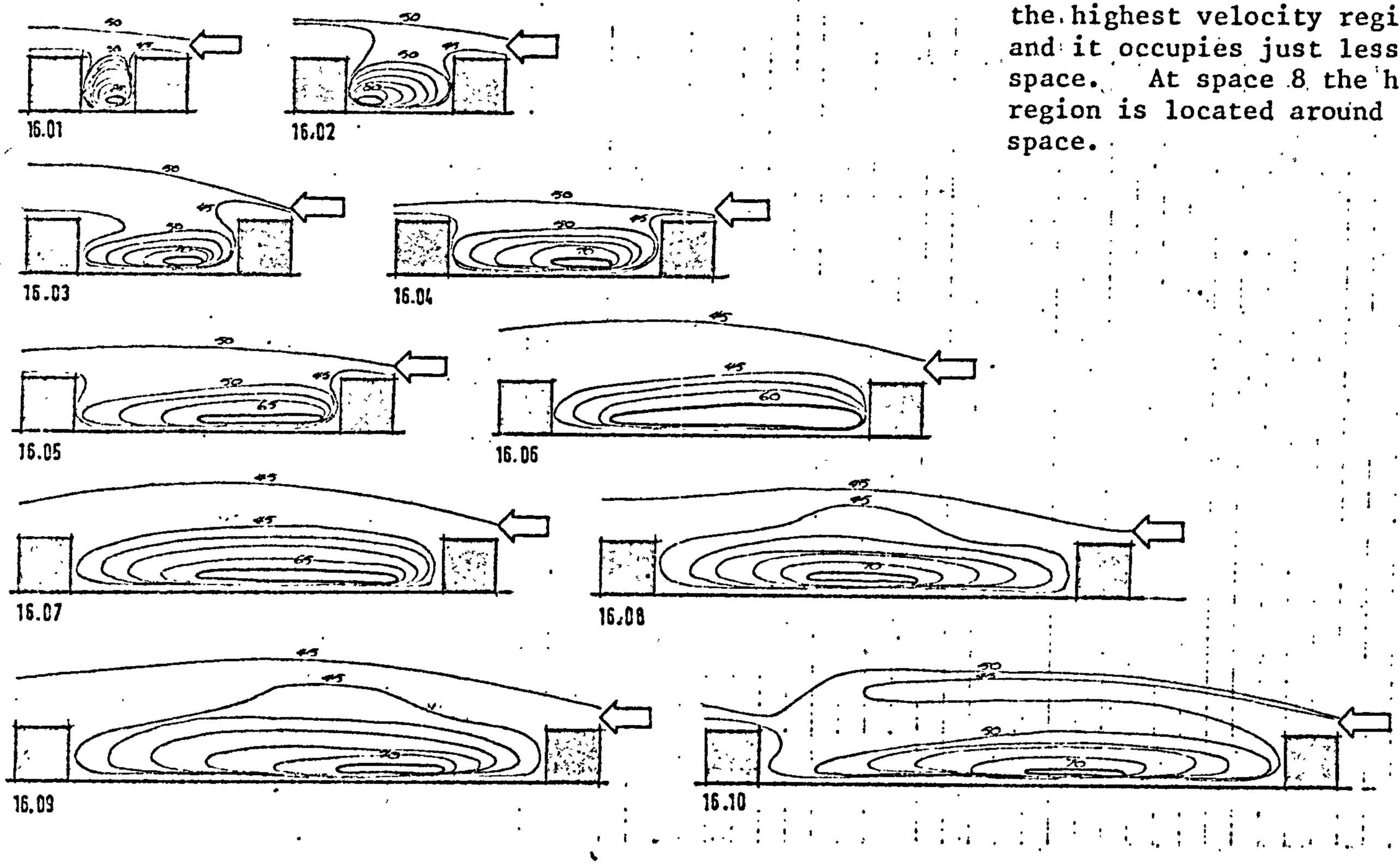


DIAGRAM 3.20: FLOW PATTERNS AT BLOCK LENGTH 16 ($\theta = 0°$)

The maximum highest velocity, 85%, occurs at space 1 with its position shifted to the upwind end. For some spaces the values of the highest velocities drop from previous values (spaces 3,5,6, and 8). At space 6 the highest velocity region is the largest and it occupies just less than half the space. At space 8 the highest velocity region is located around the centre of the space.

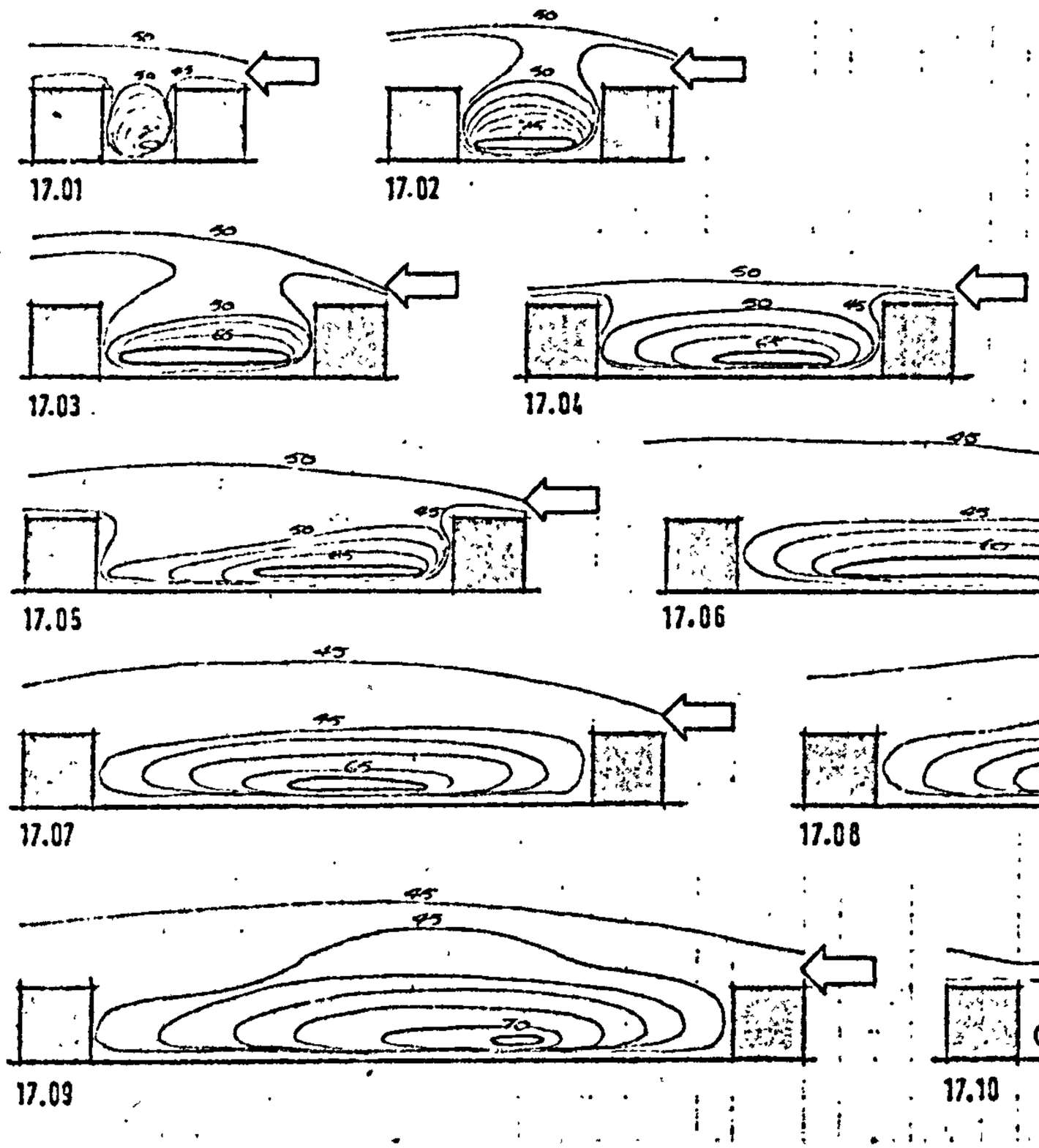


DIAGRAM 3.21: FLOW PATTERNS AT BLOCK LENGTH 17 (θ = 0°)

The most significant change in this case is the reduction in value and change in size and position of the highest velocity regions at spaces 2 and 3. At space 2 its value drops to 75% and it expands horizontally across the space with a substantial increase in area. For space 3 a similar change occurs with a drop in value to 65%. At spaces 7, 8 and 10 the highest velocity regions locate around the centre of the space.

This arrangement shows no significant change from the precious one apart from slight changes in some of the sizes of the highest velocity regions.

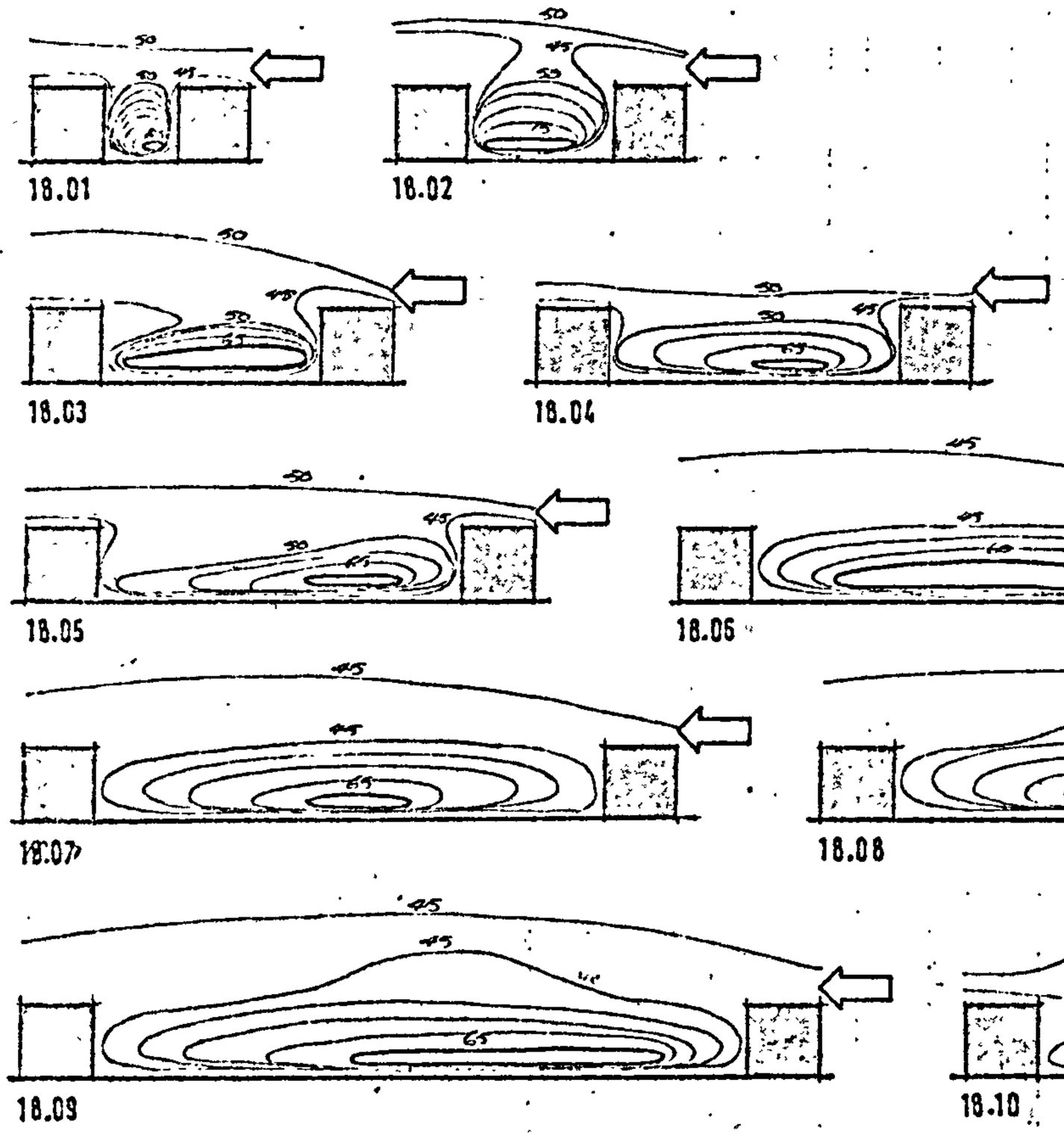


DIAGRAM 3.22: FLOW PATTERNS AT BLOCK LENGTH 18 (θ = 0°)

In this arrangement the flow patterns are essentially the same as in the previous case.

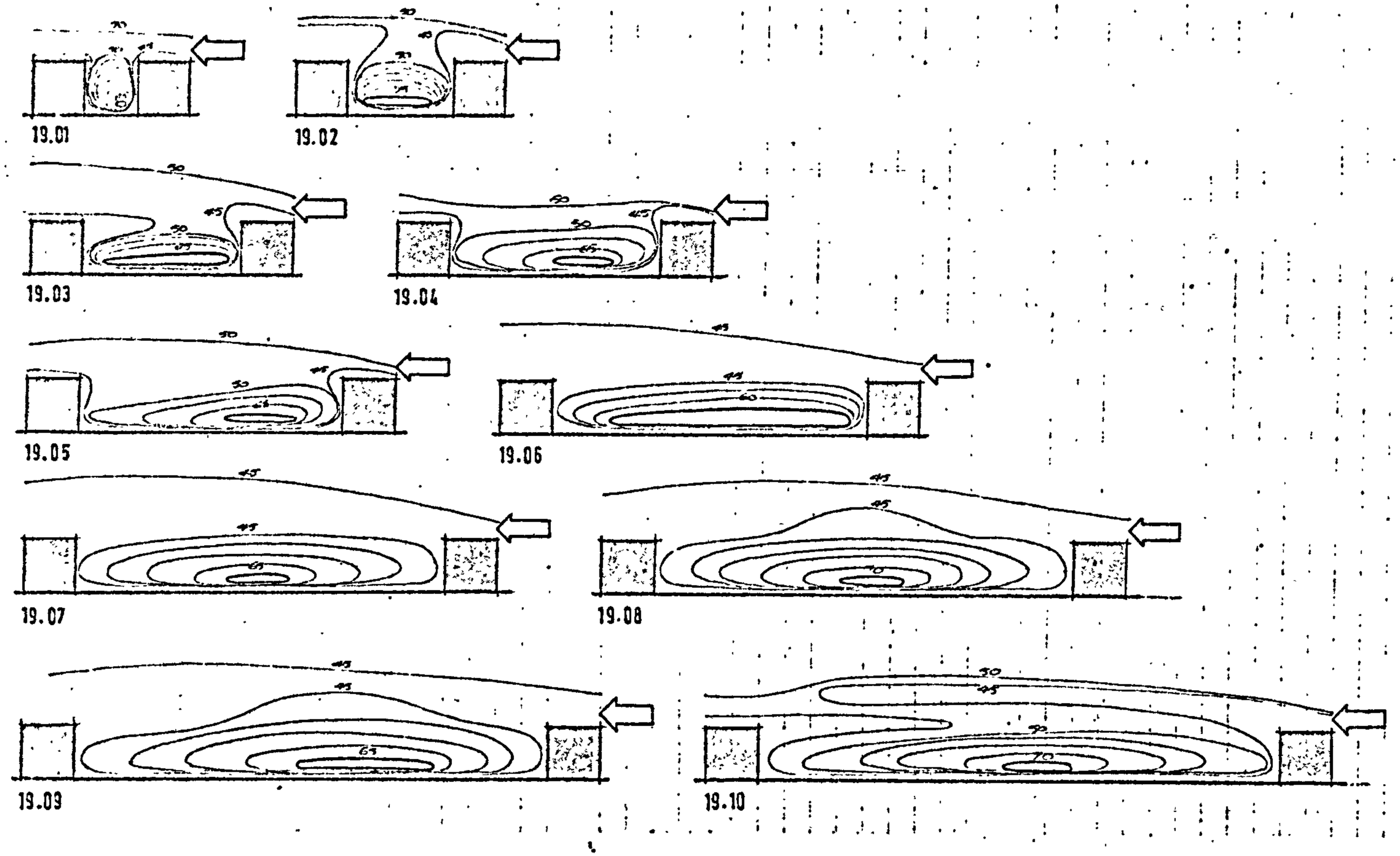


DIAGRAM 3.23: FLOW PATTERNS AT BLOCK LENGTH 19 (θ= 0°)

This arrangement shows the same patterns as the previous arrangement.

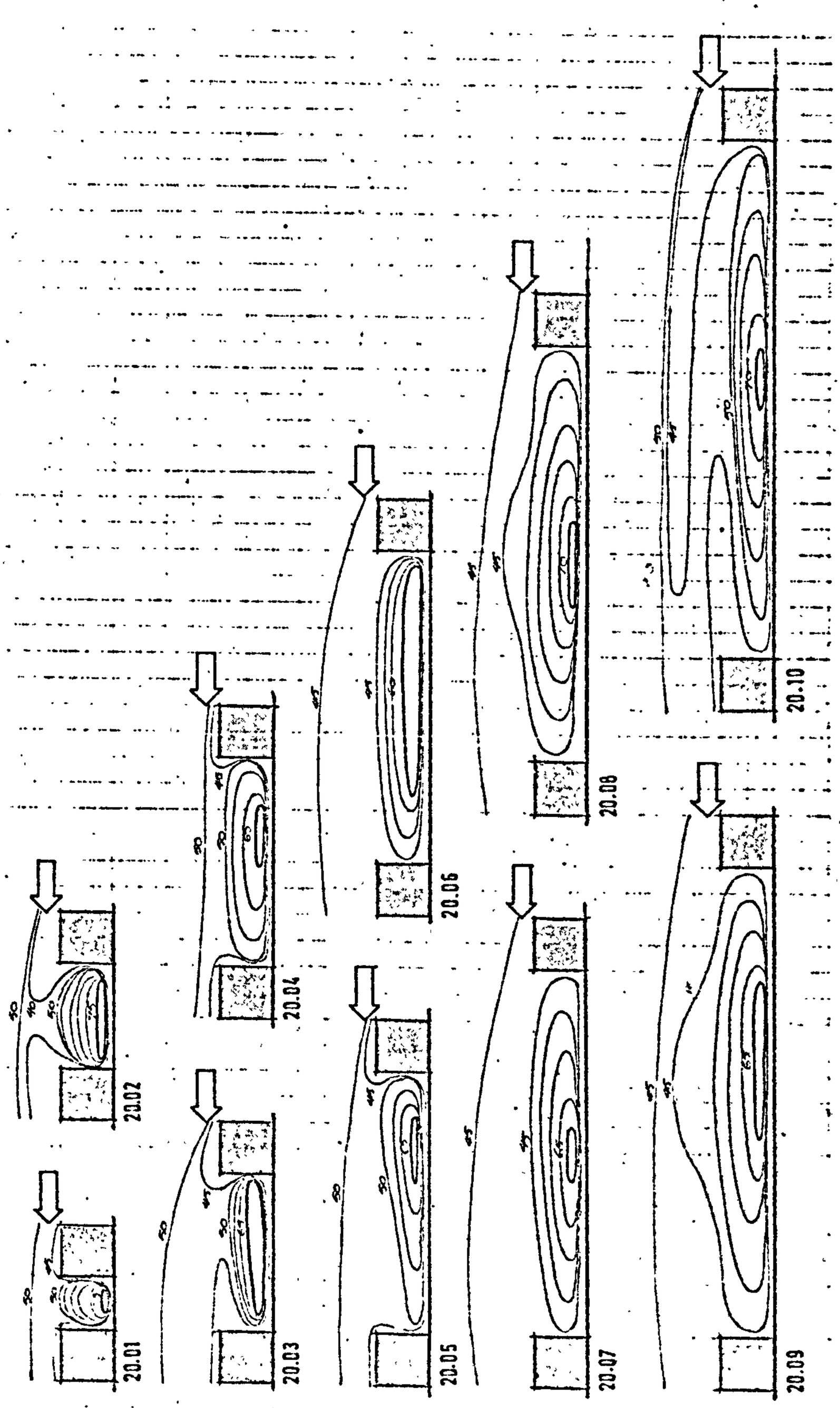


DIAGRAM 3.24: FLOW PATTERNS AT BLOCK LENGTH 20 ($\theta = 0°$)

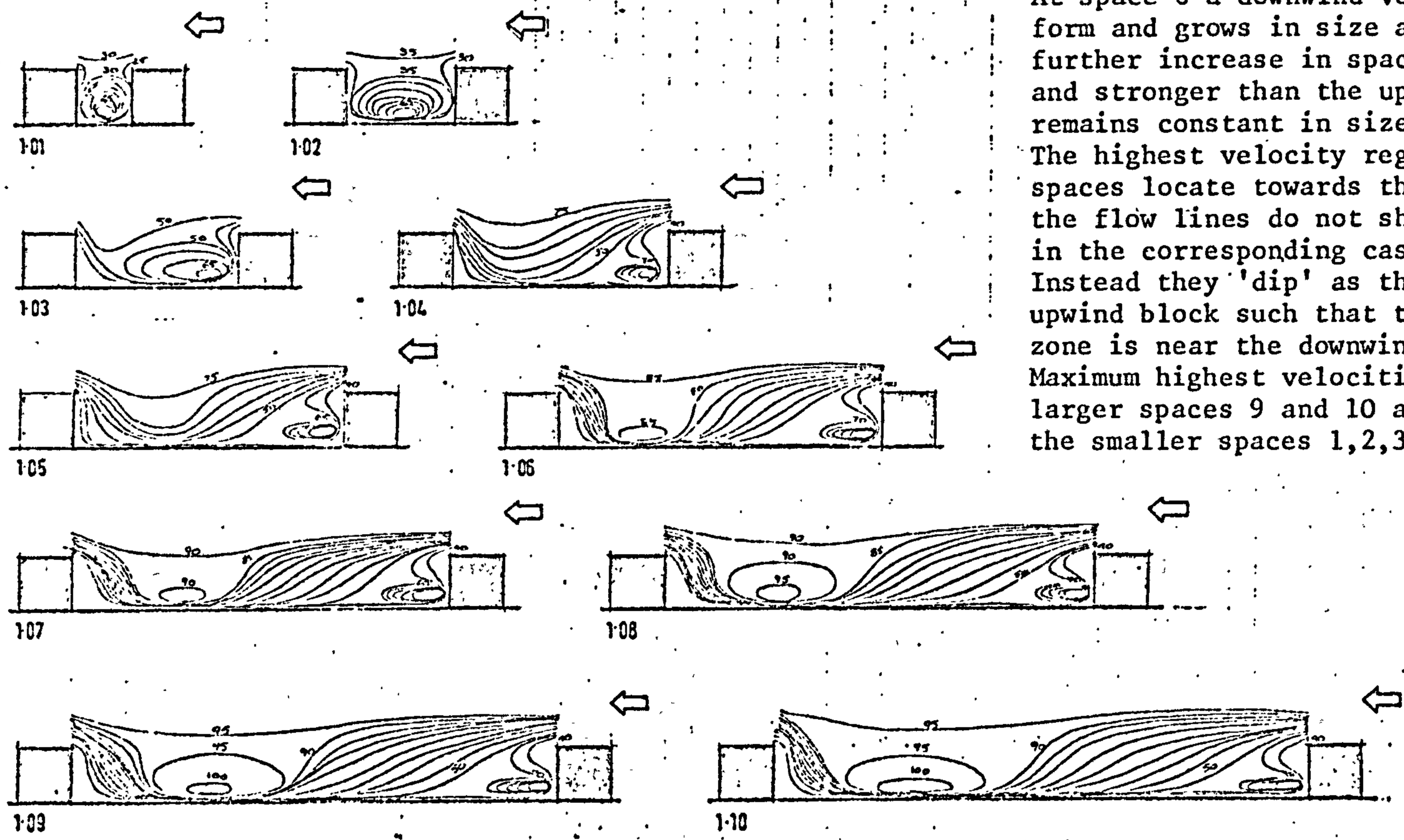


DIAGRAM 3.25: FLOW PATTERNS AT BLOCK LENGTH·1 ($\theta = 30^{\circ}$)

At this oblique orientation the smaller spaces permit the formation of a vortex filling the space. This vortex shrinks with increase in space and this shrinkage is most pronounced between spaces 3 and 4. At space 6 a downwind vortex begins to form and grows in size and strength with further increase in space. It is larger and stronger than the upwind vortex which remains constant in size after space 3. The highest velocity regions for larger spaces locate towards the downwind end and the flow lines do not show 'back-turns' as in the corresponding case when $\theta=0^{\circ}$. Instead they 'dip' as the flow passes the upwind block such that the highest velocity zone is near the downwind end of the space. Maximum highest velocities occur at the larger spaces 9 and 10 and the minimum at the smaller spaces 1,2,3 and 4.

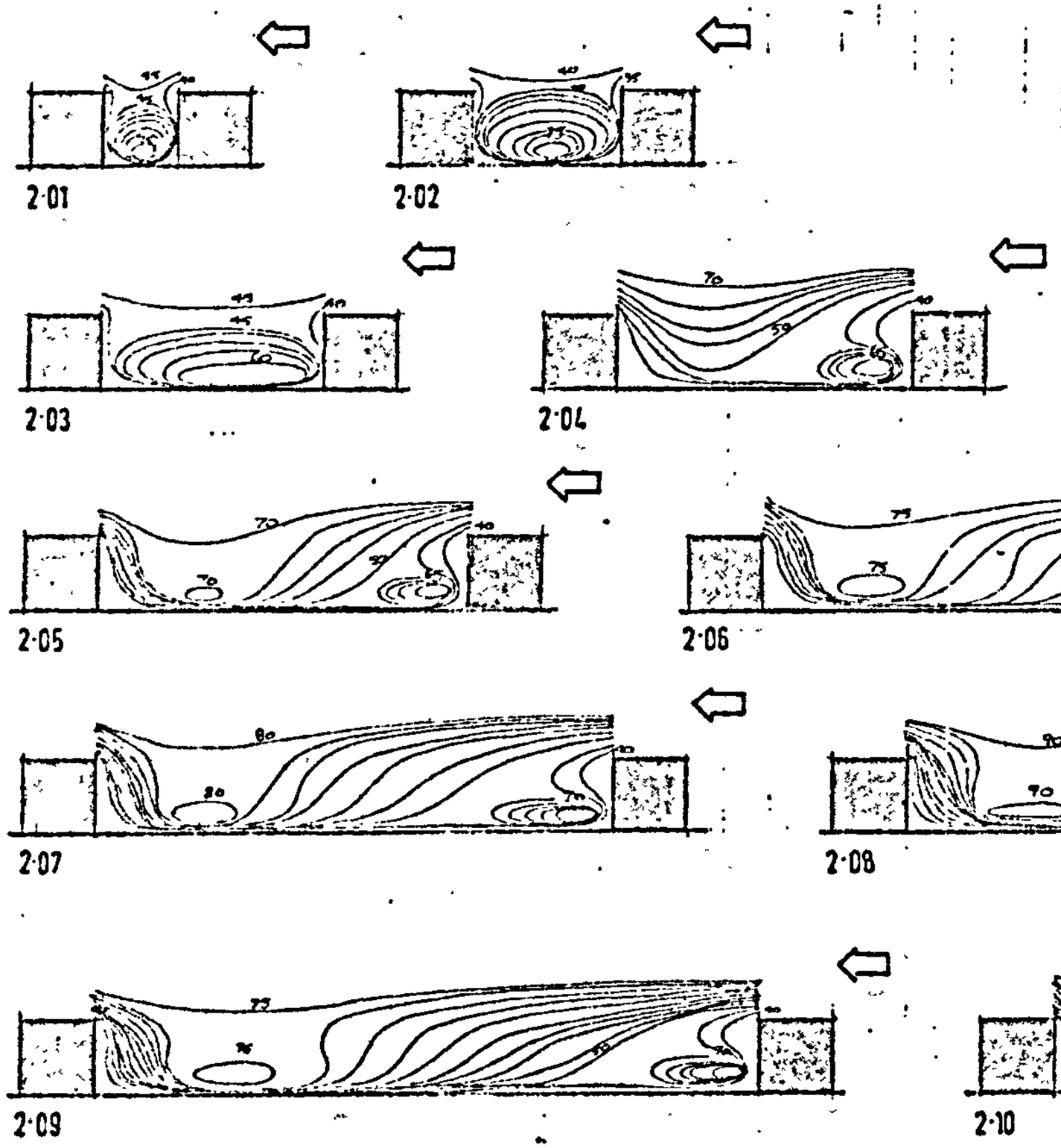


DIAGRAM 3.26: FLOW PATTERNS AT BLOCK LENGTH 2 ($\theta = 30°$)

A space filling vortex forms at the smaller spaces. The emergence of a downwind vortex is earlier than in the previous case: at space 5. It starts much weaker than in the previous case and never reaches its size. Maximum highest velocity is 100% occuring at the downwind end of space 10. The highest velocity values drop initially as the space increases but at space 5 they start to increase accompanied by a shift of position from the upwind end to the downwind end. At spaces 1 and 2 the location of the highest velocity zones is central within the space. The dip of the flow as it passes the upwind block is initially gentle but as it approaches the highest velocity zone it becomes abrupt especially at larger spaces.

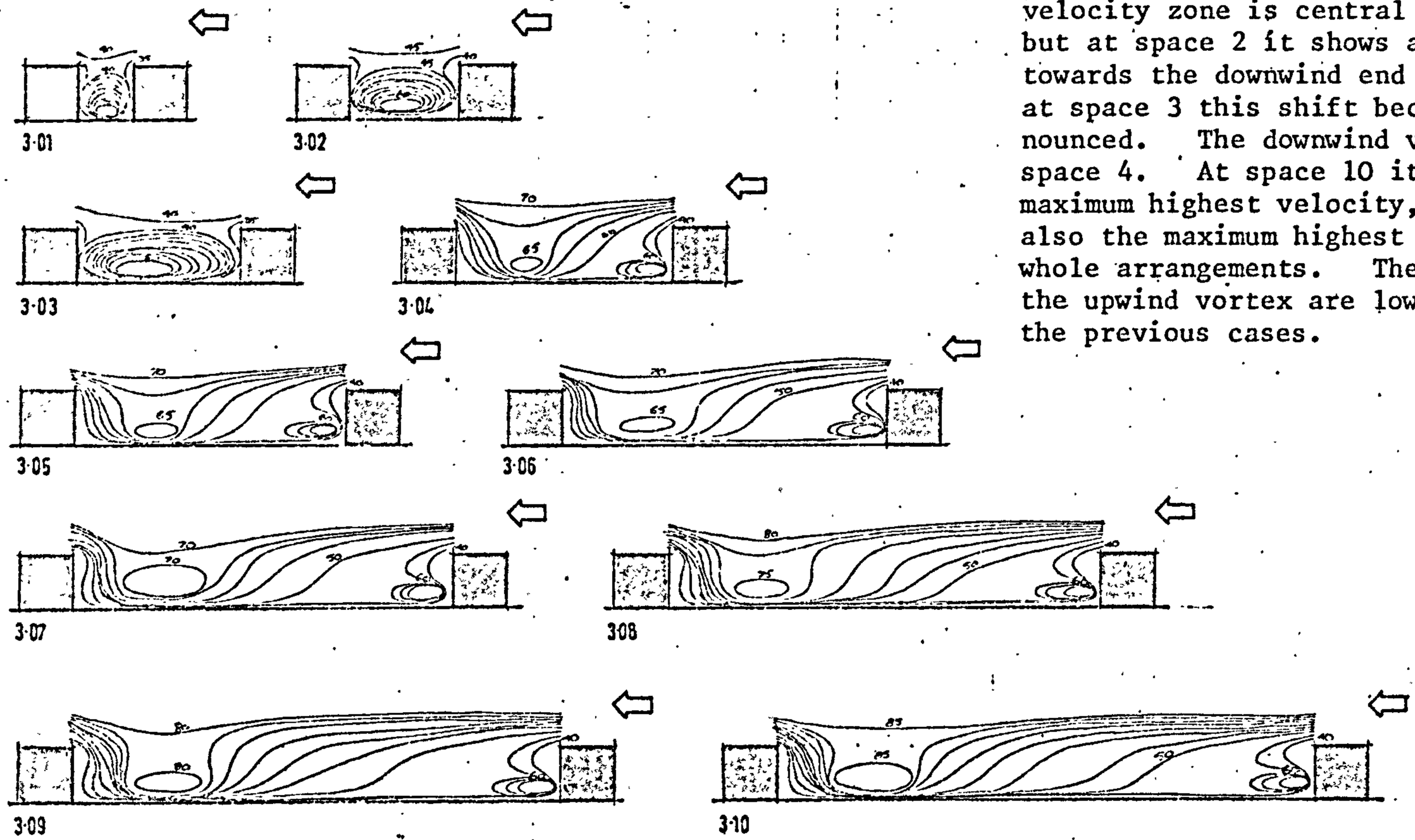
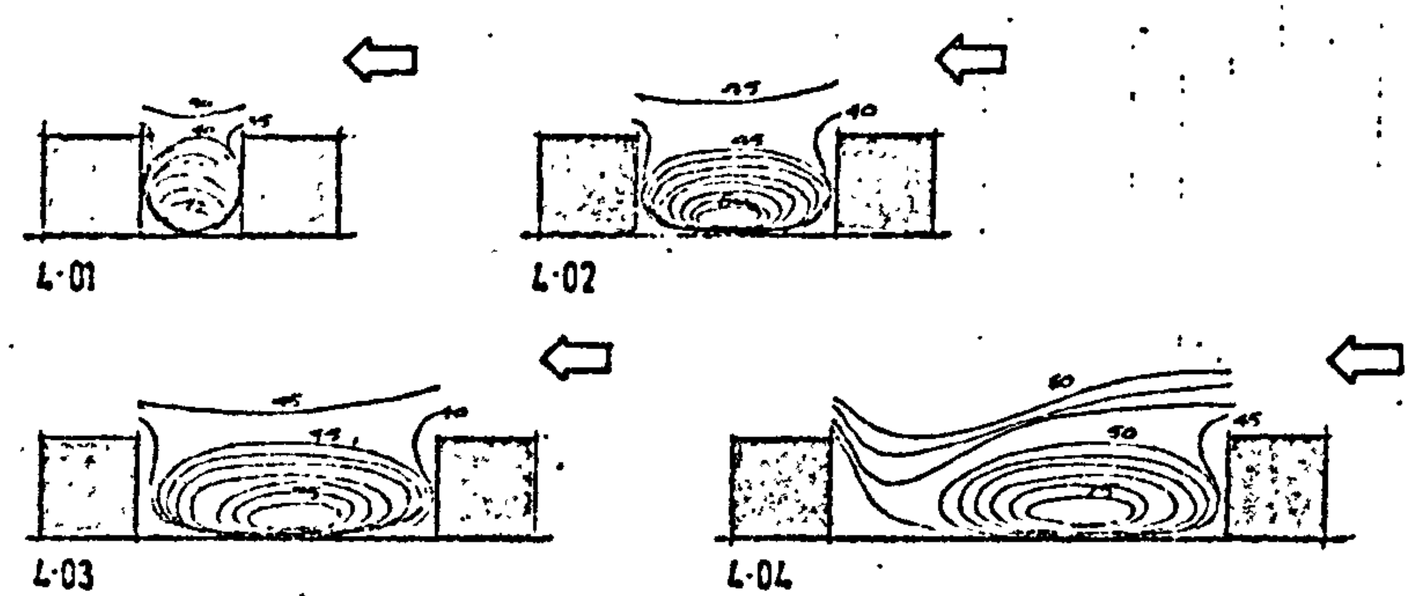


DIAGRAM 3.27: FLOW PATTERNS AT BLOCK LENGTH 3 ($\theta = 30°$)

The main developments with this increase in block length concern the position of highest velocity zones at smaller spaces, appearance of the downwind vortex and the values of the highest velocities. At space 1 the position of the highest velocity zone is central within the space but at space 2 it shows a slight shift towards the downwind end of the space and at space 3 this shift becomes more pronounced. The downwind vortex appears at space 4. At space 10 it reaches its maximum highest velocity, 85%, which is also the maximum highest velocity for the whole arrangements. The highest values in the upwind vortex are lower than those of the previous cases.



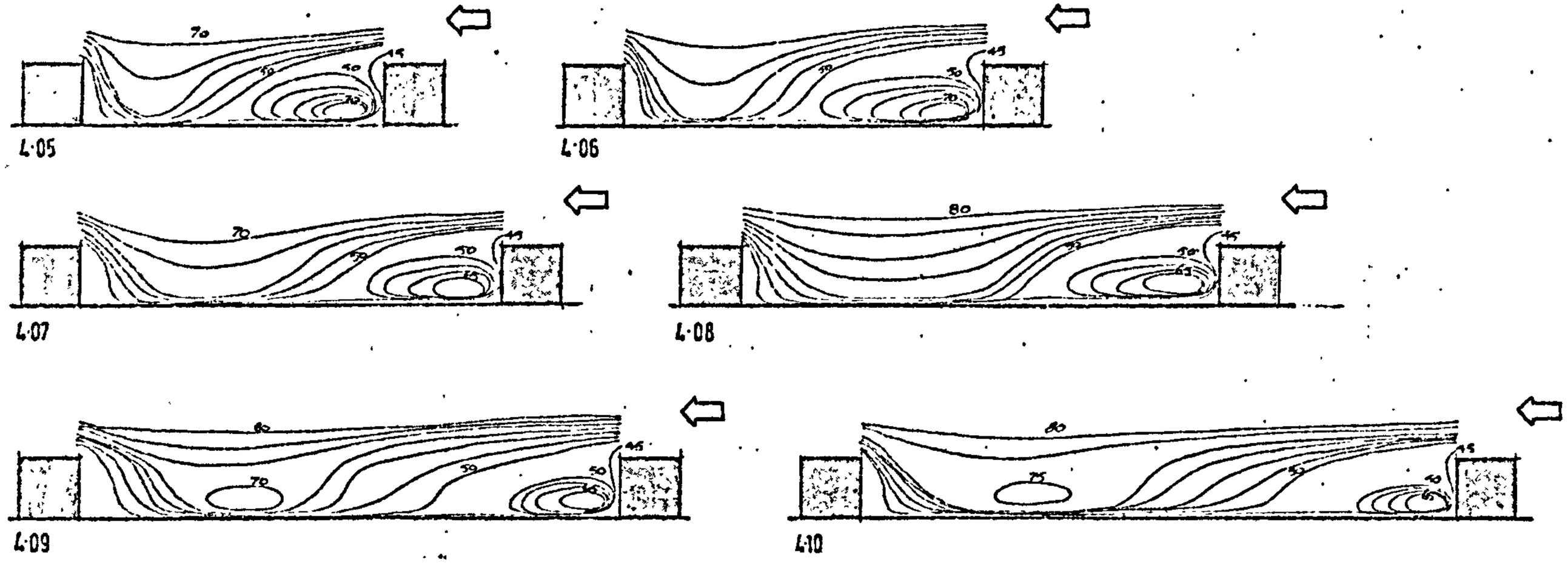


DIAGRAM 3.28: FLOW PATTERNS AT BLOCK LENGTH 4 (θ = 30°)

The increase in the relative size of the upwind vortex is the main feature of this arrangement. At space 4 it occupies more than 2/3 of the space but diminishes slowly as the space increases. The downwind vortex disappears in the intermediate space sizes but emerges at the larger spaces 9 and 10 with a much lower value of highest velocity than previously. The position of the highest velocity zones moves from the downwind end at smaller spaces to the upwind end at intermediate spaces but returns to the downwind end at the larger spaces 9 and 10. The maximum highest velocity value is 80% occuring at space size 2.

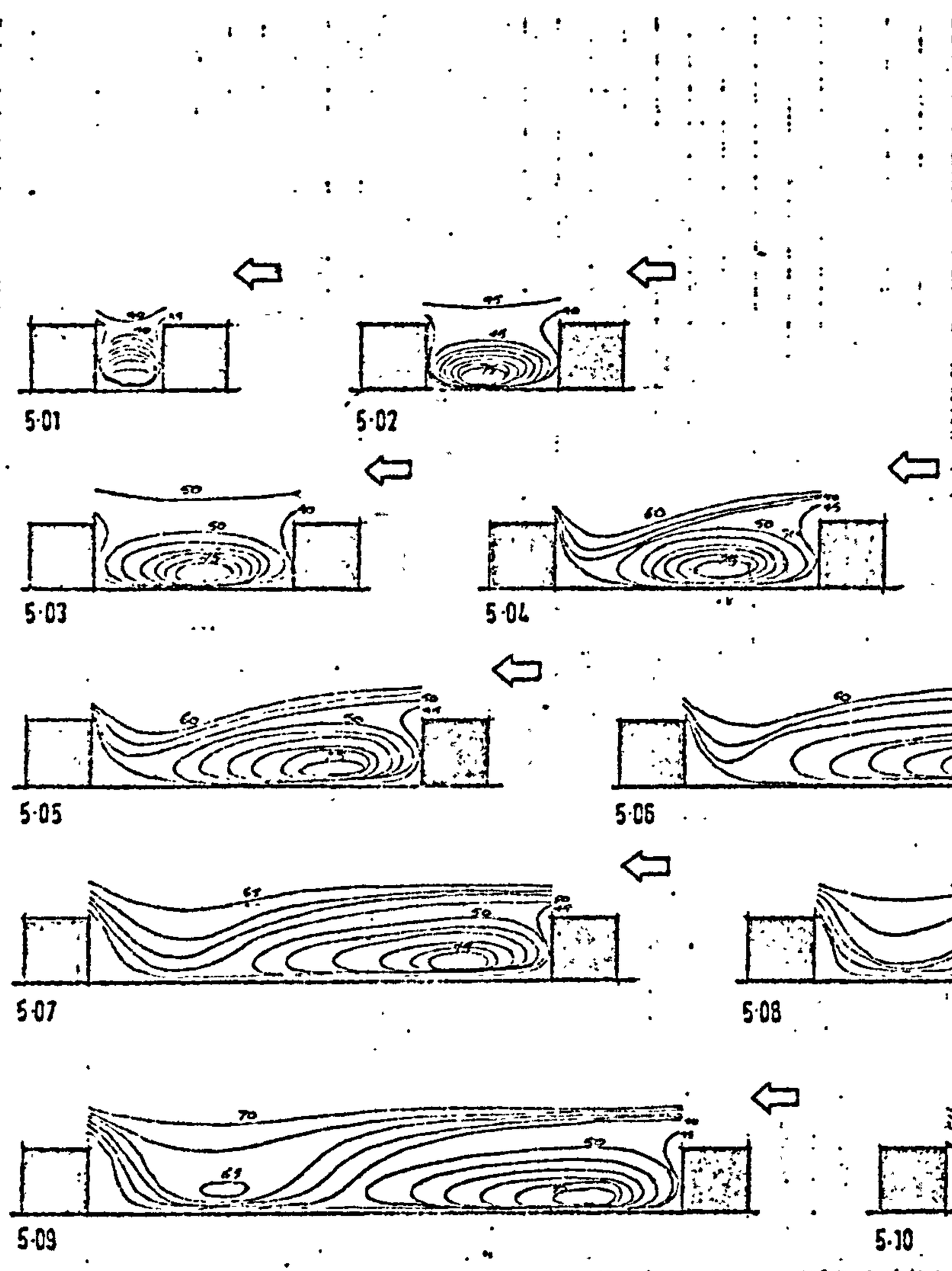


DIAGRAM 3.29: FLOW PATTERNS AT BLOCK LENGTH 5 (θ = 30°)

The increase of block length in this case has two main effects: the sustenance of a stable large vortex throughout the changes in the space size. This vortex fills the space at smaller space sizes but as the space increases it locates towards the upwind end. The other effect is the shift of the position of the highest velocities from a central position within the smaller spaces towards the upwind end for the intermediate and larger spaces. At the larger spaces 9 and 10, however, a small, weak second vortex appears at the downwind end of the space. The highest velocity is the same throughout. The extent to which the dip of the flow varies can be illustrated by following the 60% contour: it is attracted to the bottom of the space at the downwind end as the space size increases. The size of the vortex, however, does not change substantially with the increase in space after space size 4.

Apart from the increase in the highest velocity value at space 1 this arrangement shows no significant developments beyond the patterns shown by the previous case.

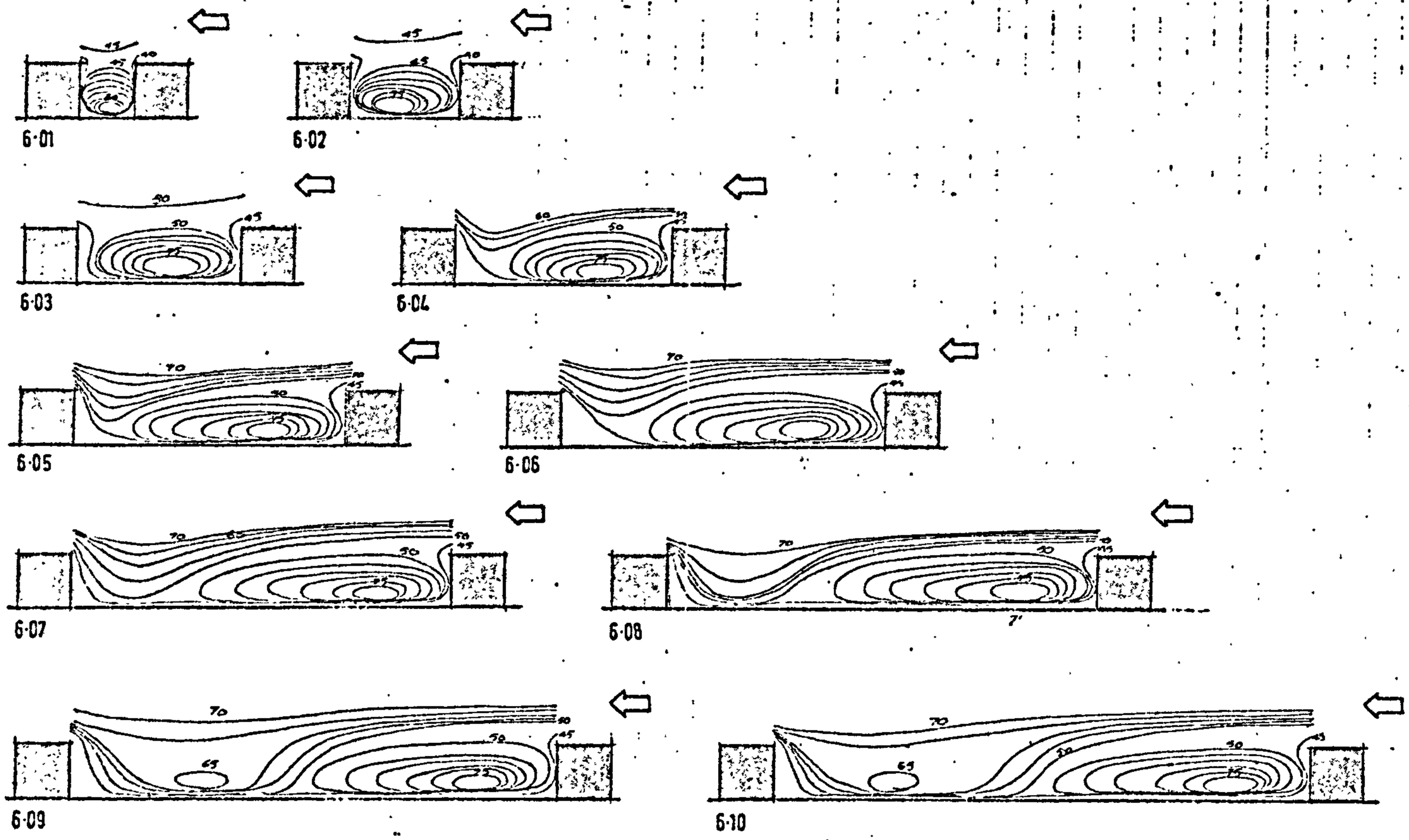


DIAGRAM 3.30: FLOW PATTERNS AT BLOCK LENGTH 6 ($\theta = 30°$)

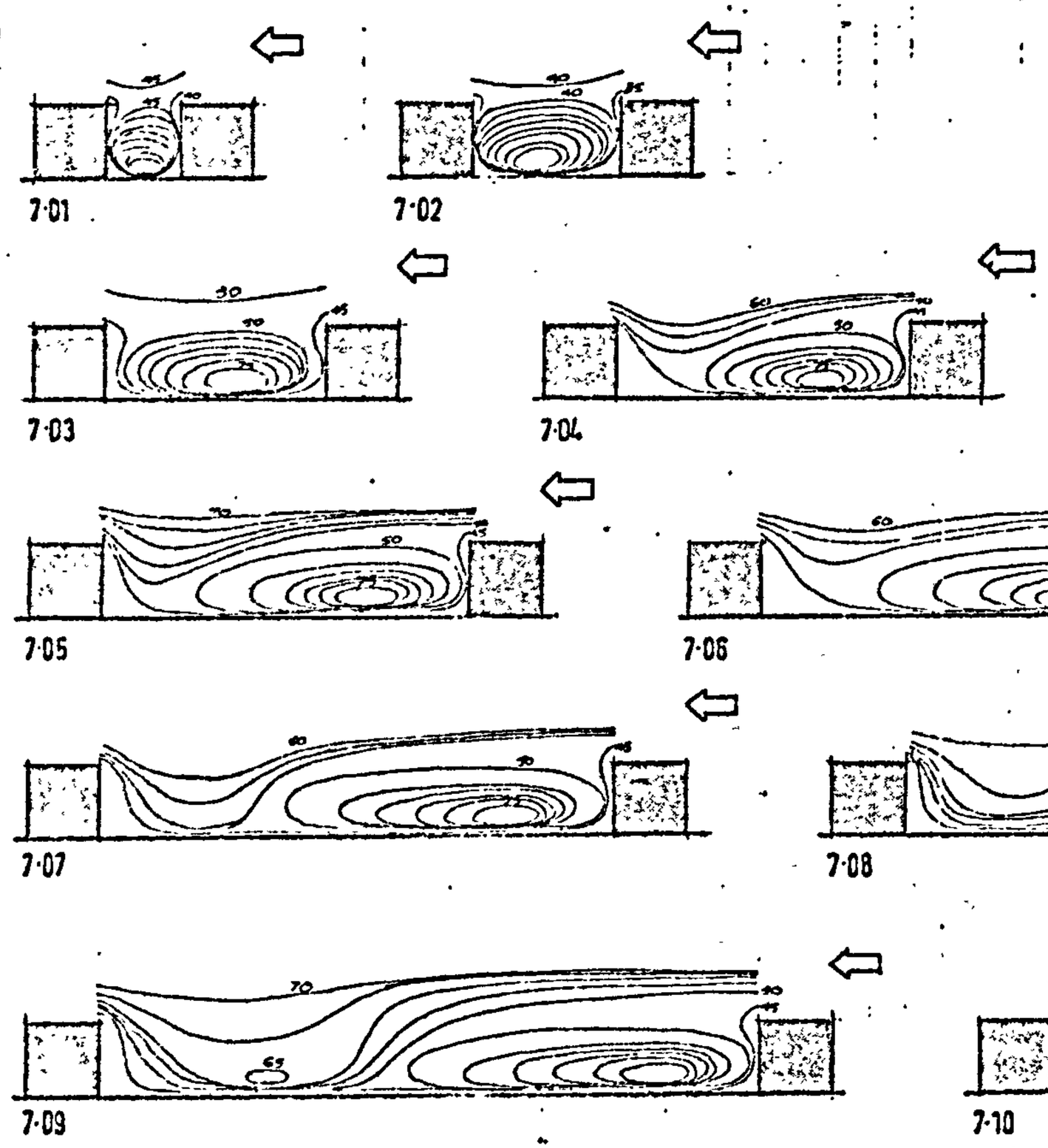


DIAGRAM 3.31: FLOW PATTERNS AT BLOCK LENGTH 7 (θ = 30°)

In this case the patterns are generally very much like the previous case. There are, however, some changes in the larger space 10 where the downwind vortex disappears with a substantial dip of the 70% contour into the space.

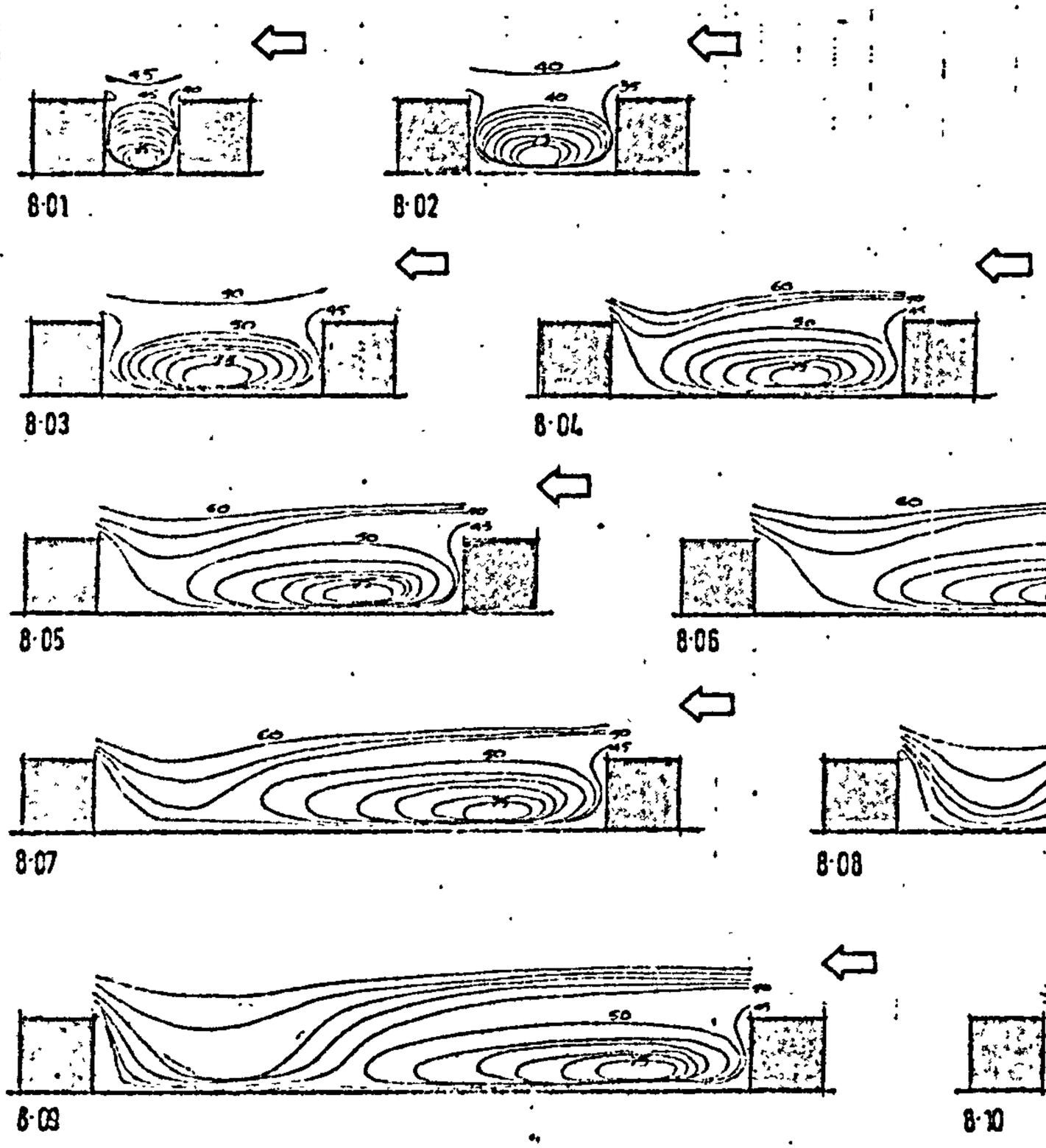
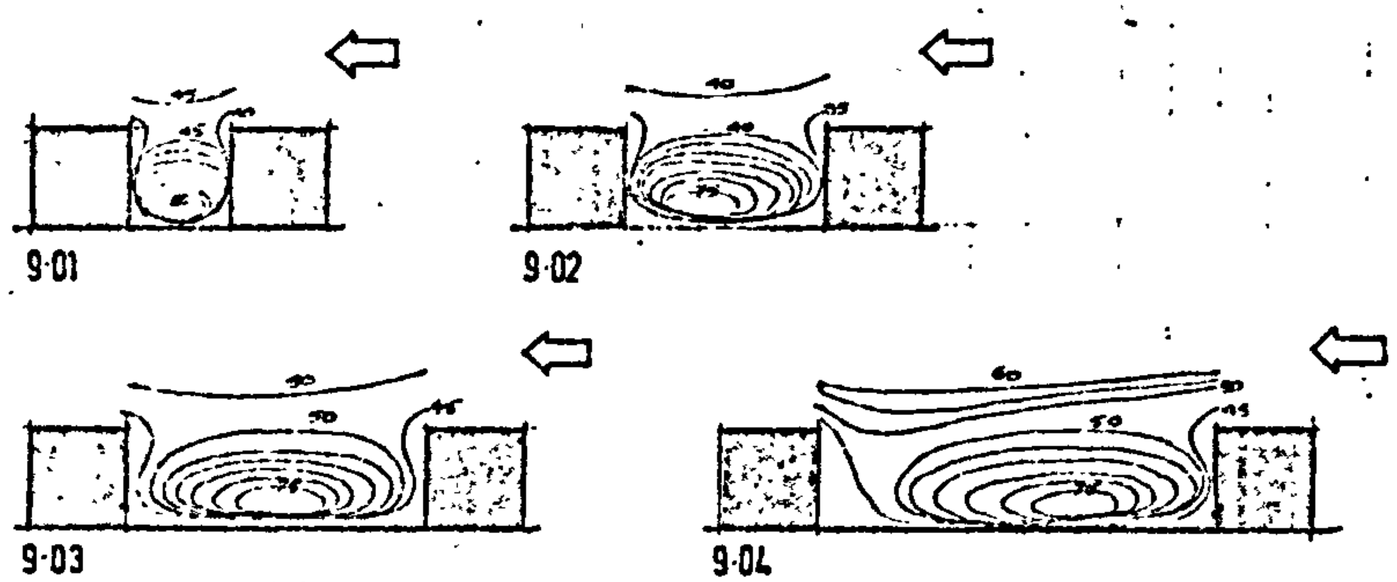


DIAGRAM 3.32: FLOW PATTERNS AT BLOCK LENGTH 8 ($\theta = 30°$)

In this case there is a total absence of any downwind vortex. The highest velocity region moves from a central position within the smaller spaces to locate near the upwind block with increase in space. The maximum highest velocity occurs at space 1 and the minimum occurs at space 10 with the space sizes in between having a constant 75% highest velocity value. So far, and after block length 5, the changes in the patterns with change in block length have been slow and occured only for the larger spaces. Further increases in block length will be seen to be even less effective to bring about substantial changes in the flow patterns.



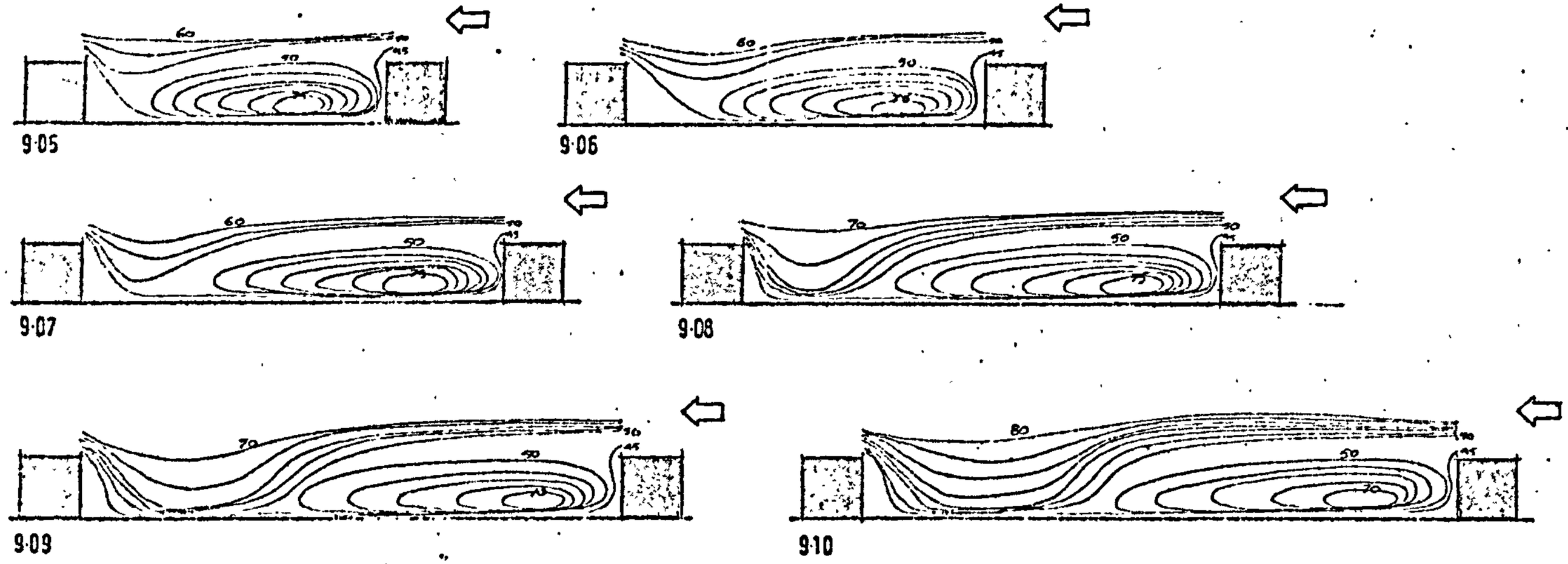


DIAGRAM 3.33: FLOW PATTERNS AT BLOCK LENGTH 9 (θ = 30°)

The main changes in this case occur in some of the highest velocity values. At space 9 this drops to 70% and at space 1 it increases to 85% more than in the previous case. The shift of the positions of highest velocity regions and the sizes of the vortices remain the same.

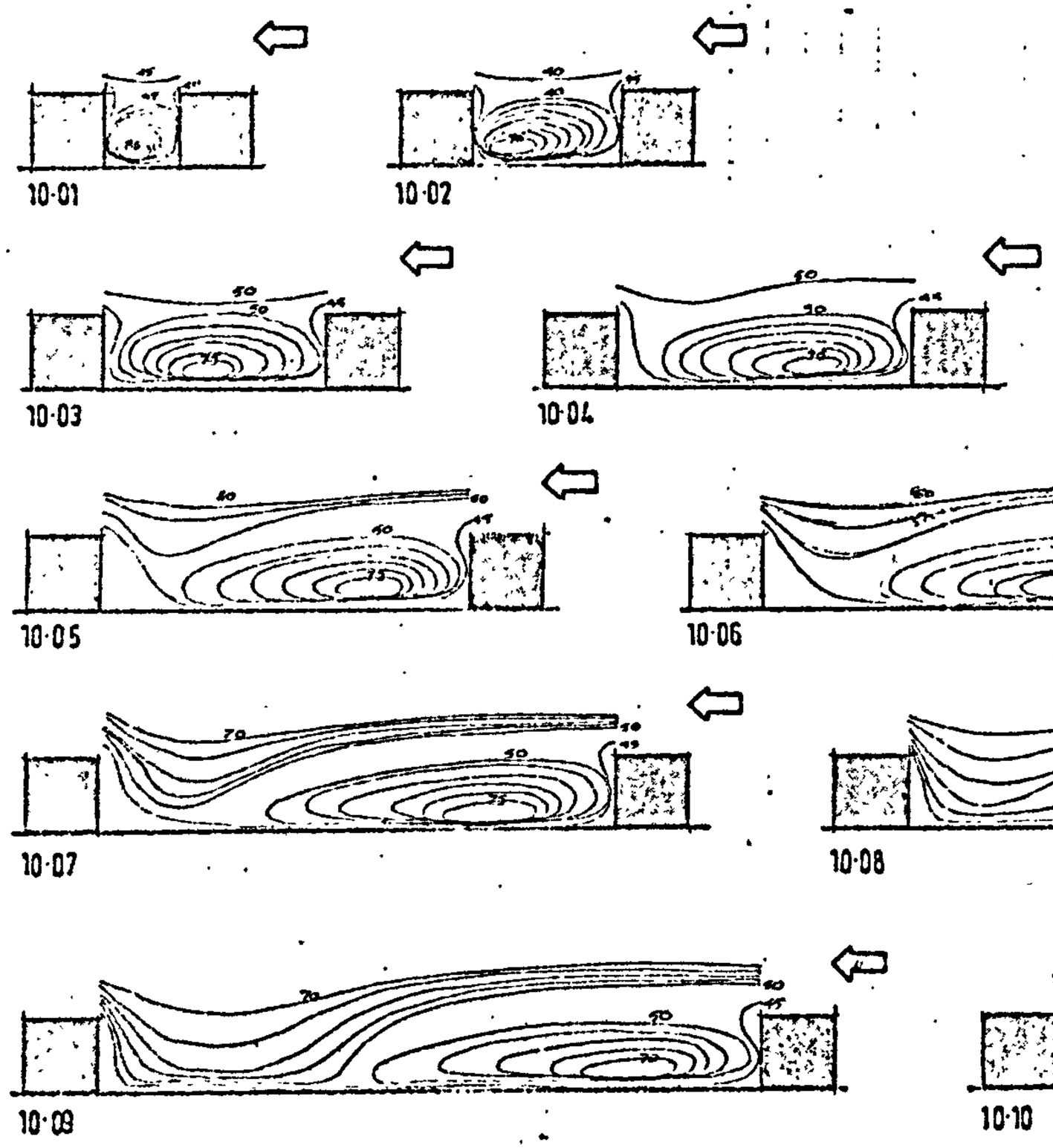


DIAGRAM 3.34: FLOW PATTERNS AT BLOCK LENGTH 10 (θ =30°)

At this block length the positions of highest velocity regions move from a downwind position at space 1 towards the upwind end as the space increases. The maximum highest velocity is 85% occuring at space 1 and the minimum highest velocity is 70% occuring at spaces 9 and 10.

This arrangement shows the same patterns as in the previous block length with some differences in the positions of speed contours and changes in their values.

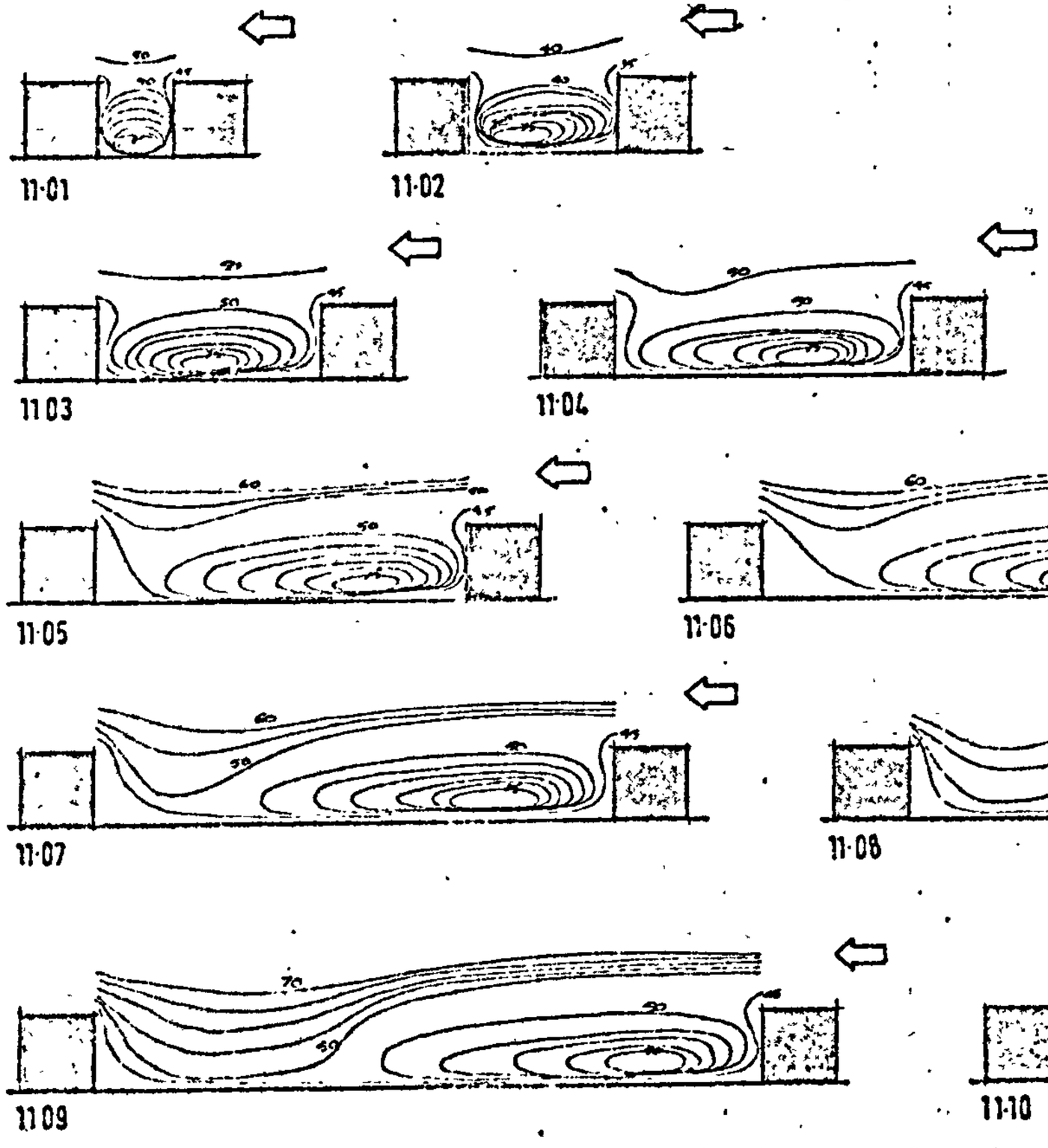


DIAGRAM 3.35: FLOW PATTERNS AT BLOCK LENGTH 11 ($\theta = 30°$)

In this and the following arrangements the main changes concern the values of the highest velocities; but the patterns remain basically the same as in the past few cases.

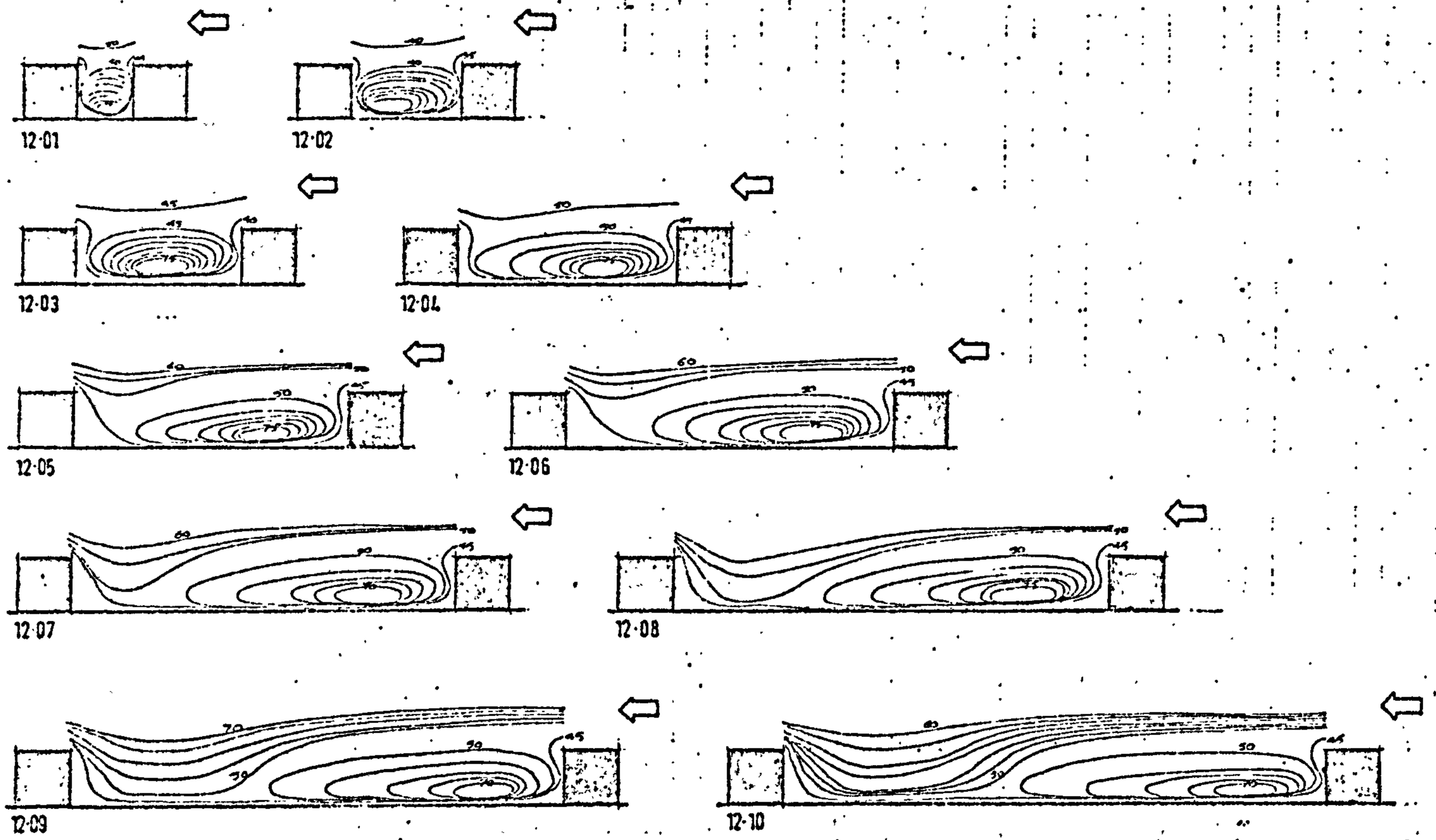


DIAGRAM 3.36: FLOW PATTERNS AT BLOCK LENGTH 12 (θ = 30°)

See Diagram 3.36 for comment.

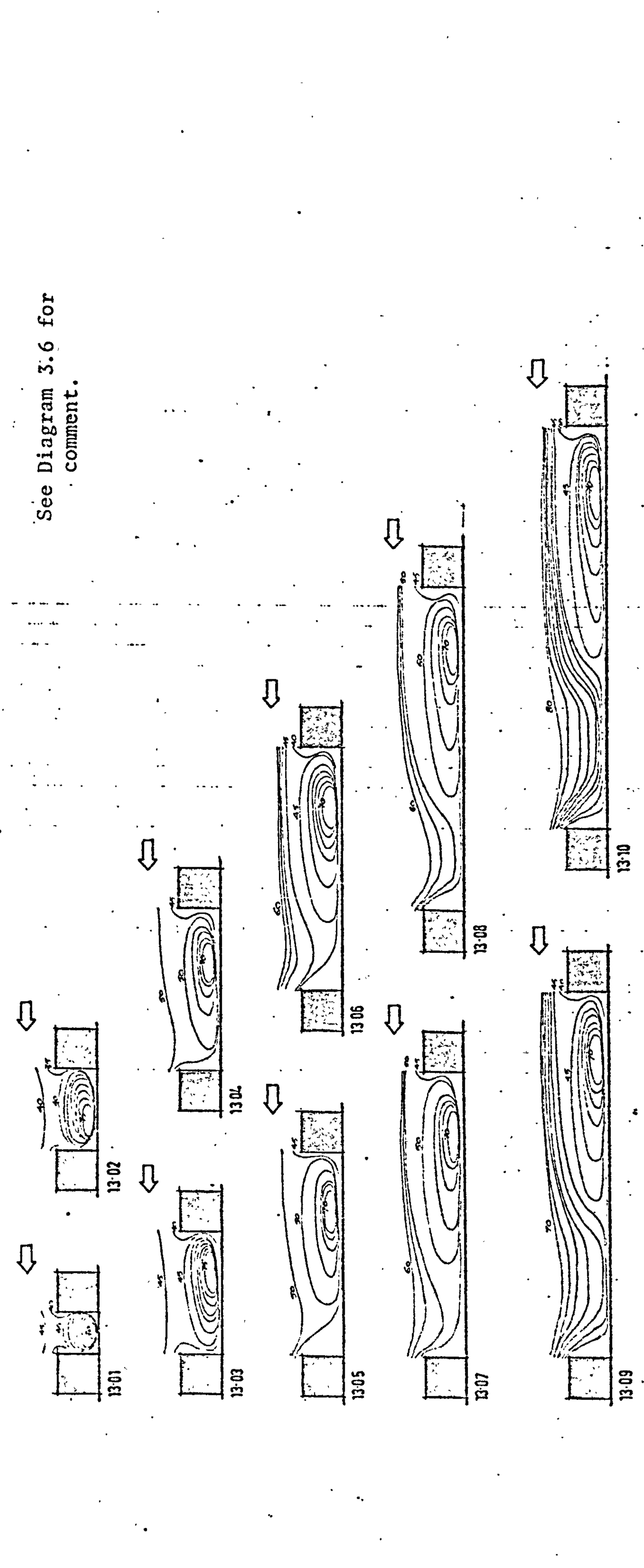


DIAGRAM 3.37: FLOW PATTERNS AT BLOCK LENGTH 13 ($\theta = 30°$)

See Diagram 3.36 for comment.

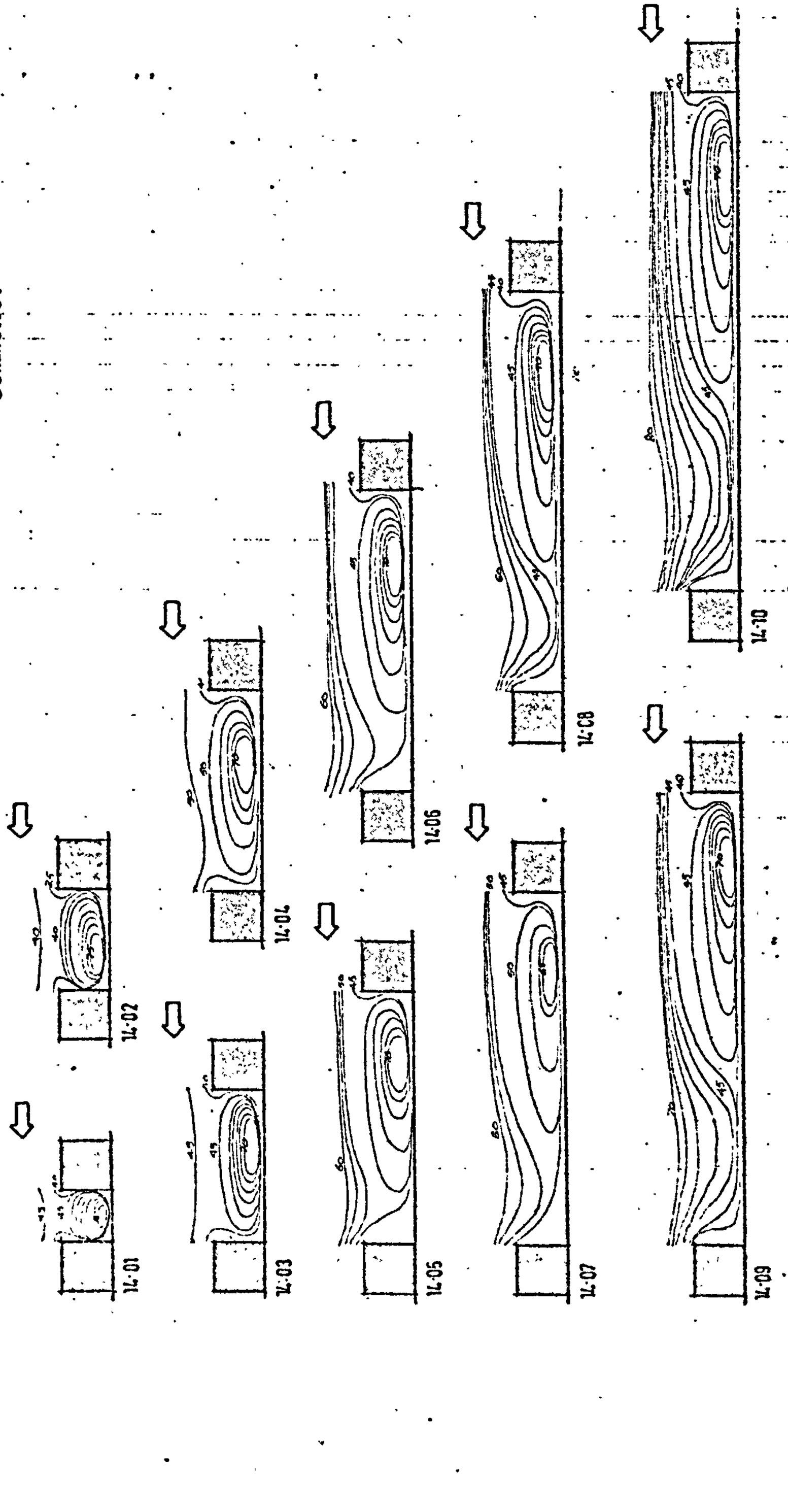


DIAGRAM 3.38: FLOW PATTERNS AT BLOCK LENGTH 14 (θ = 30°)

See Diagram 3.36 for comment.

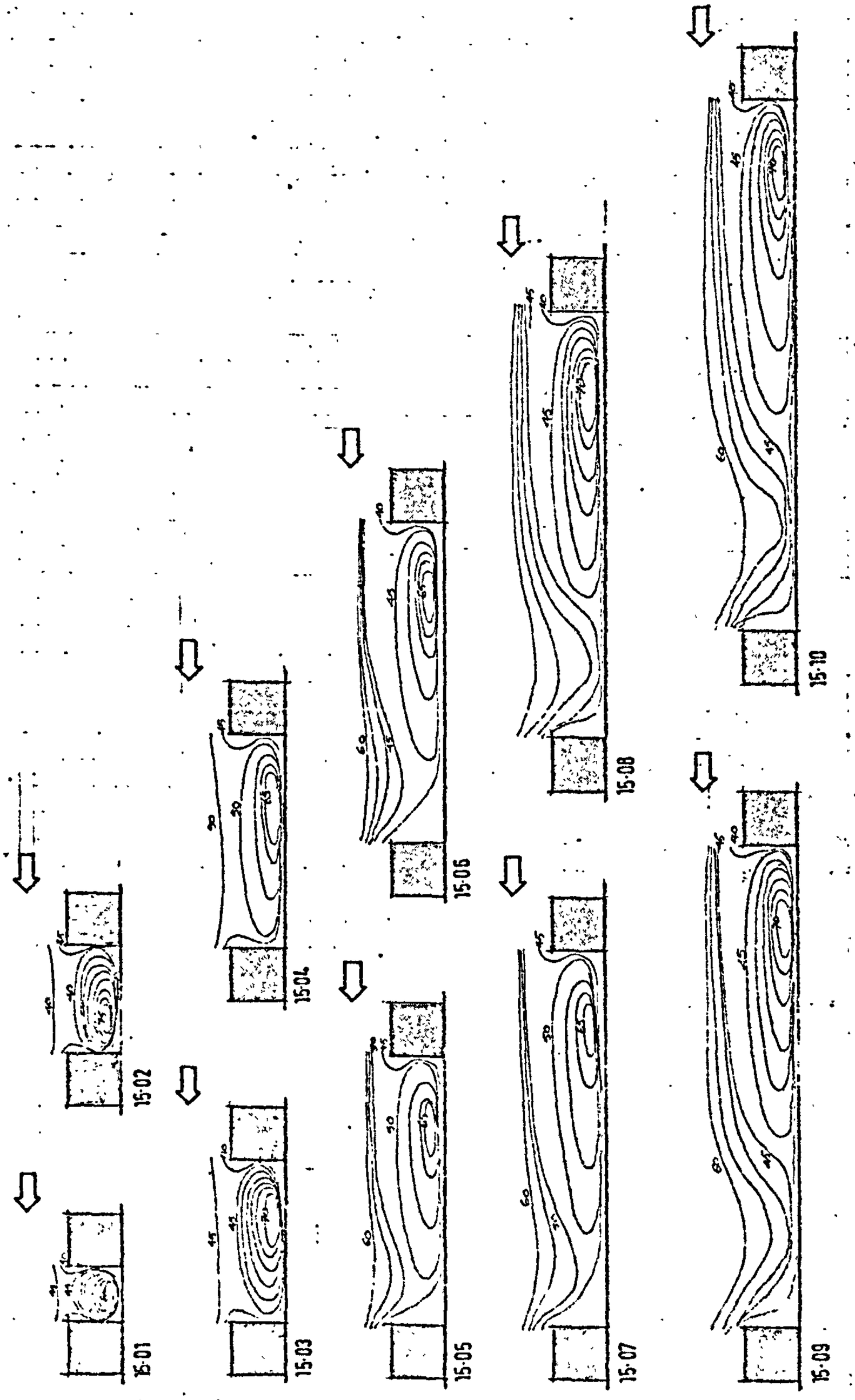


DIAGRAM 3.39: FLOW PATTERNS AT BLOCK LENGTH 15 (θ = 30°)

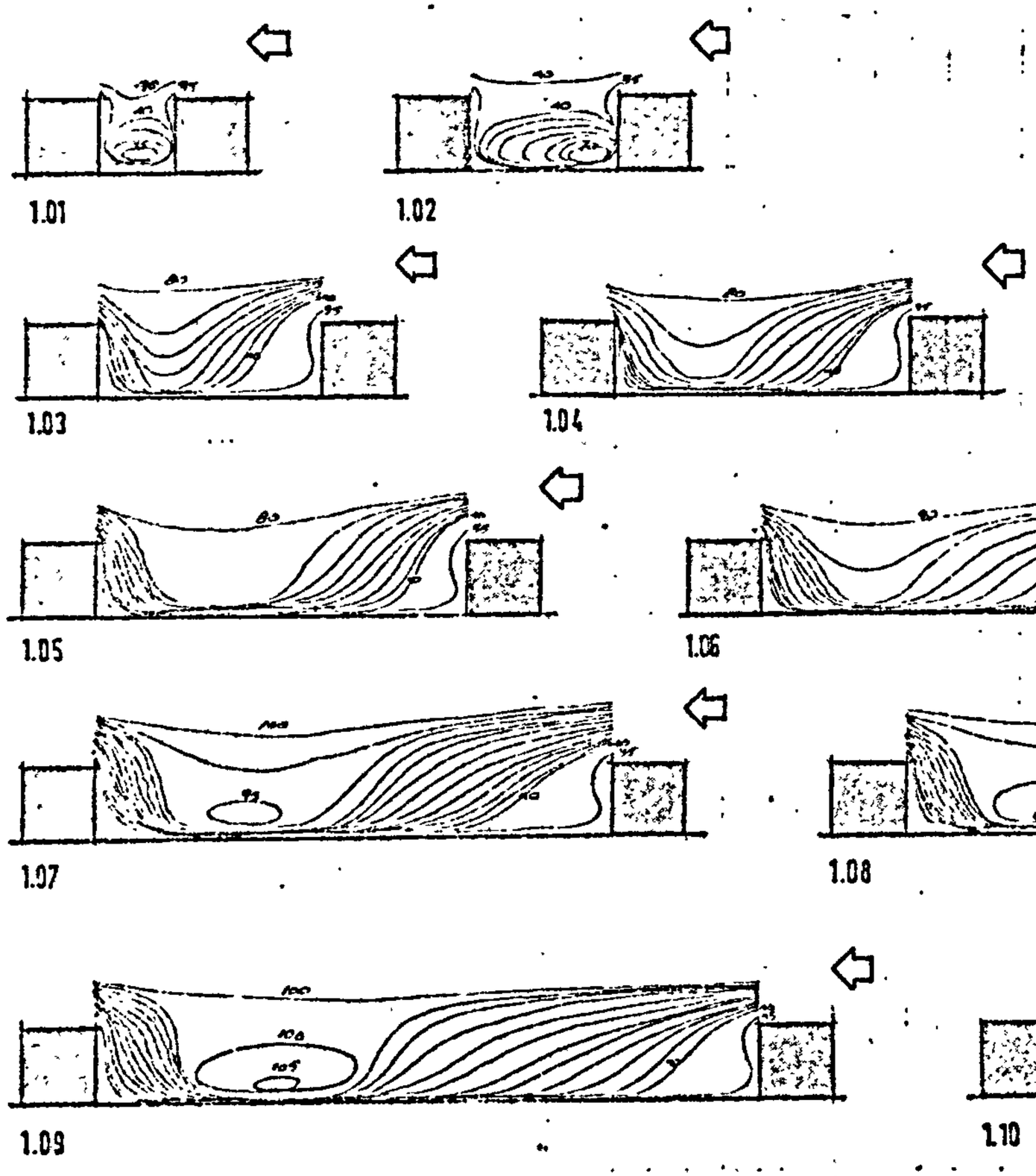


DIAGRAM 3.40: FLOW PATTERNS AT BLOCK LENGTH 1 ($\theta = 45°$)

The increase in the obliqueness of orientation leads to the disappearance of an upwind vortex which prevailed previously in corresponding arrangements. Moreover intermediate spaces (3,4,5,6) show no vortices in the flow pattern. A space filling vortex exists only at the smaller spaces 1 and 2 and downwind vortices appear in the larger spaces 7,8,9 and 10. The maximum highest velocity occurs at spacing 10 and the minimum occurs at spacing 1. The speed contours where no space-filling vortex exists, dip to the lower levels towards the downwind end of the space. The downwind vortex increases in intensity and size as the space increases from 7 to 10.

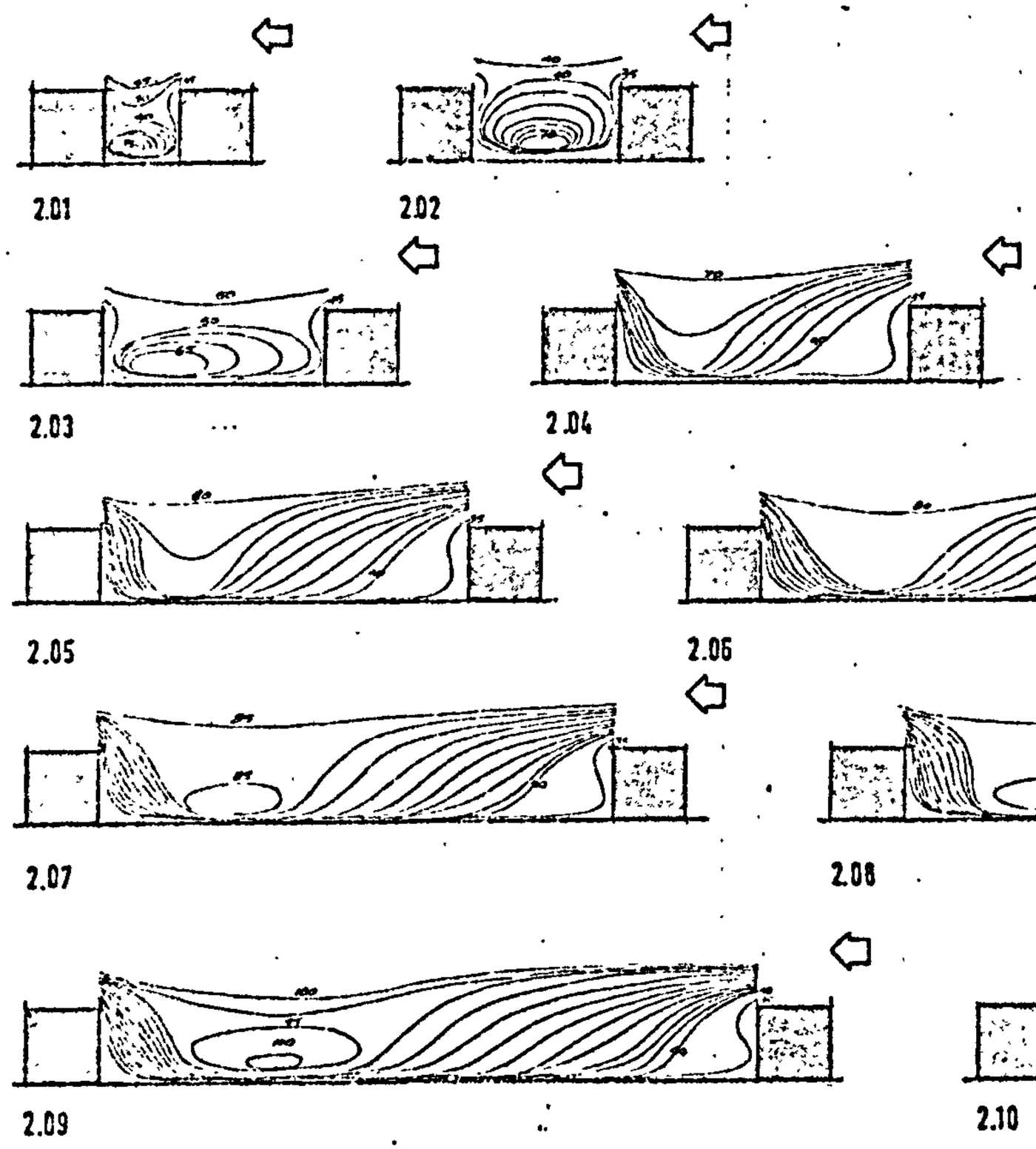


DIAGRAM 3.41: FLOW PATTERNS AT BLOCK LENGTH 2 (θ = 45°)

The increase of block length in this case has three main effects: prolonging the existence of the space filling vortex to space 3, increasing the value of the minimum highest velocity and reducing the value of the maximum highest velocity relative to the previous case. The intermediate spaces 4, 5 and 6 show no vortices while the downwind vortices at spaces 7,8,9 and 10 are sustained but with reduced intensity. Thespeed contours, as in the previous case, dip towards the downwind end of the space.

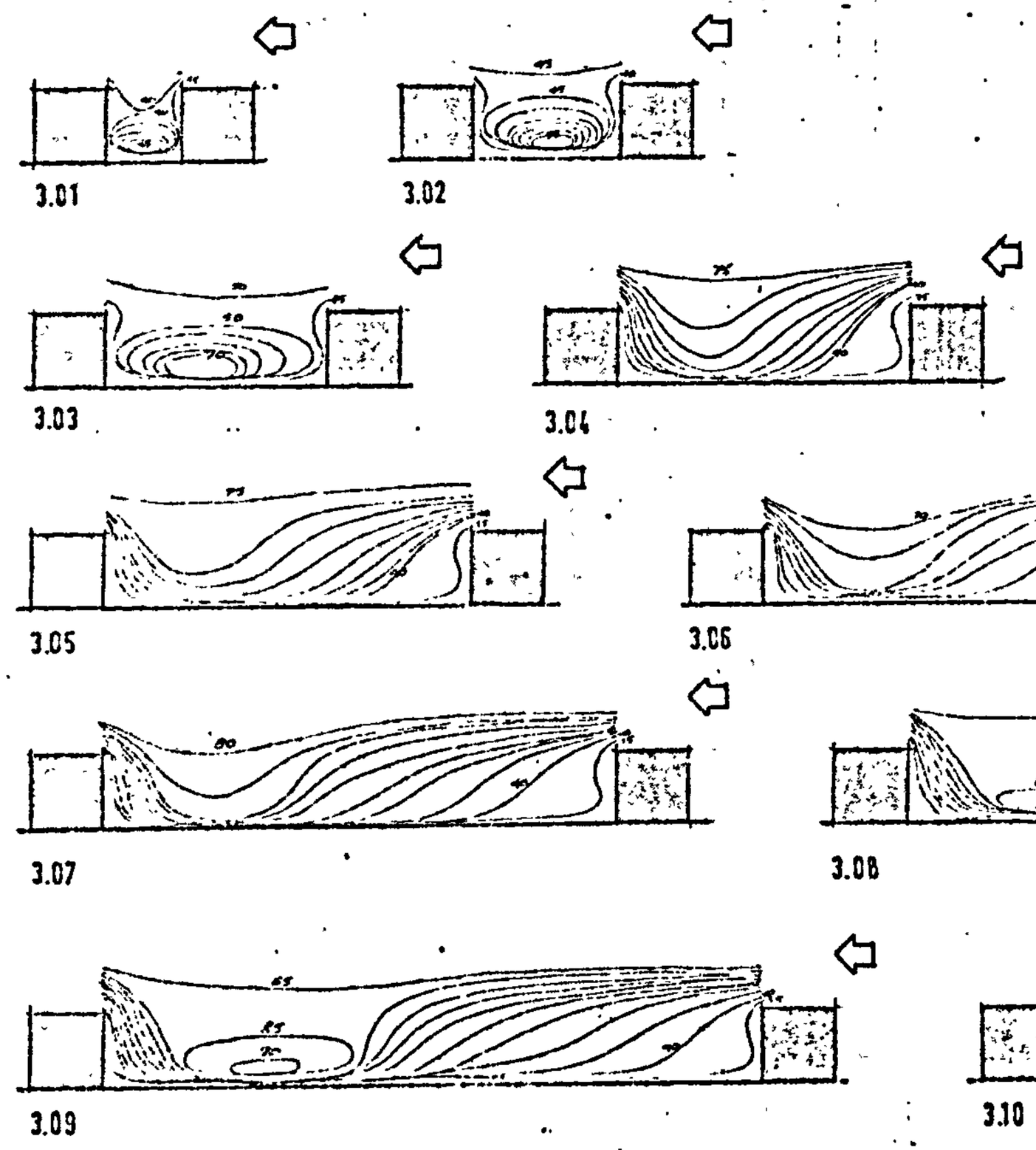


DIAGRAM 3.42: FLOW PATTERNS AT BLOCK LENGTH 3 ($\theta = 45°$)

The main developments in increasing the space size here is the delay in the appearance of the downwind vortex, increase in the minimum highest velocity value and a decrease in the value of the maximum highest velocity. One space filling vortex is sustained in the smaller spaces 1,2, and 3 and a downwind vortex begins to appear at space 8 increasing in intensity and size as the space increases to 10. At this stage the sheltering effect of the block length with this orientation begins to be felt.

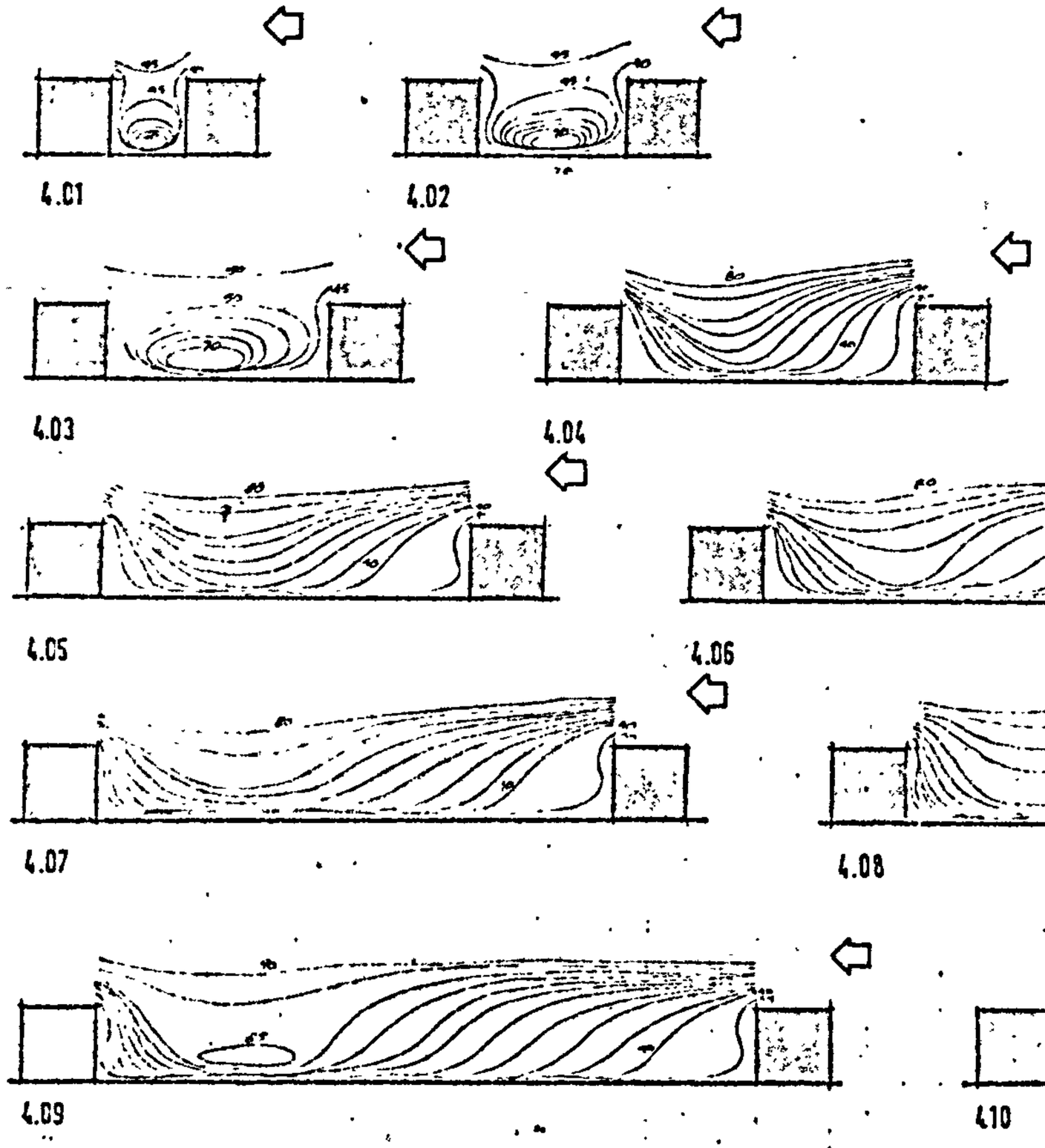


DIAGRAM 3.43: FLOW PATTERNS AT BLOCK LENGTH 4 (θ = 45°)

At this block length vortices are sustained only at the smaller spaces 1,2 and 3 (filling the space) and the larger spaces 9,10 (downwind vortices). The effect of increasing the block length is most pronounced in the case of the large space vortices: they appear only at the two largest spaces with greatly reduced size and intensity. For the intermediate spaces the flow dips towards the downwind end. The maximum highest velocity occurs at space 10 and the minimum at space 1.

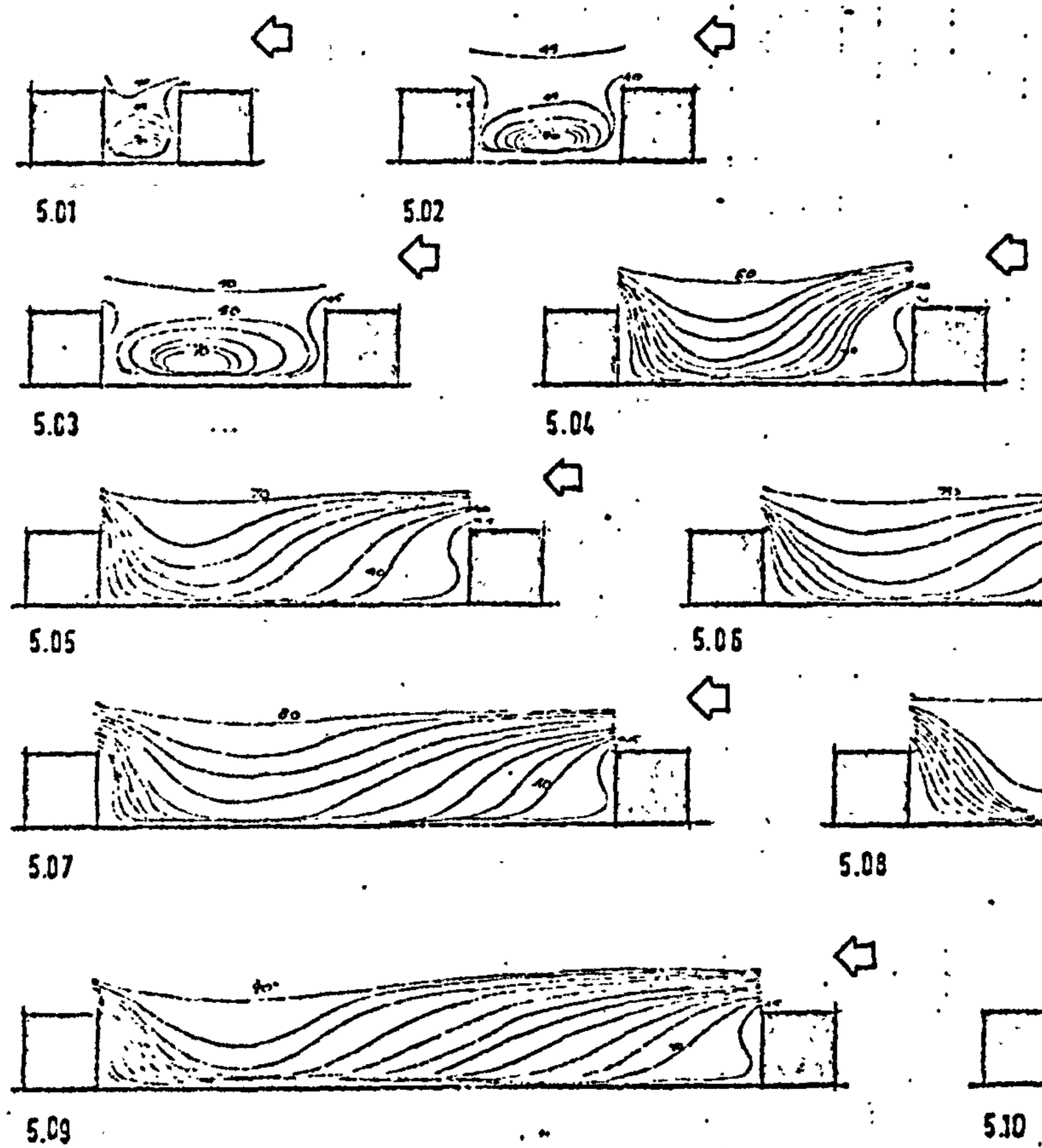
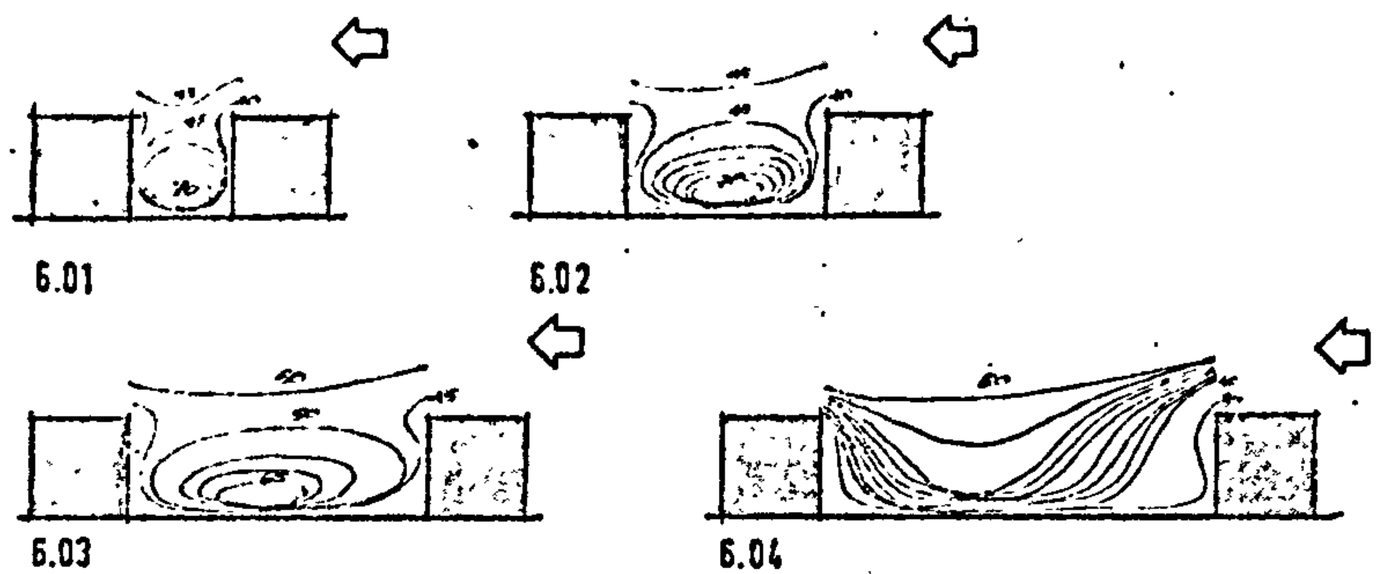


DIAGRAM 3.44: FLOW PATTERNS AT BLOCK LENGTH 5 ($\theta = 45°$)

The main development in this increase of block length affects the downwind vortex: it appears only in a greatly reduced size and intensity at the largest space 10. The smaller spaces still sustain a space-filling vortex. The minimum highest velocities occur at the smaller spaces and the maximum highest velocity occurs at the largest space.



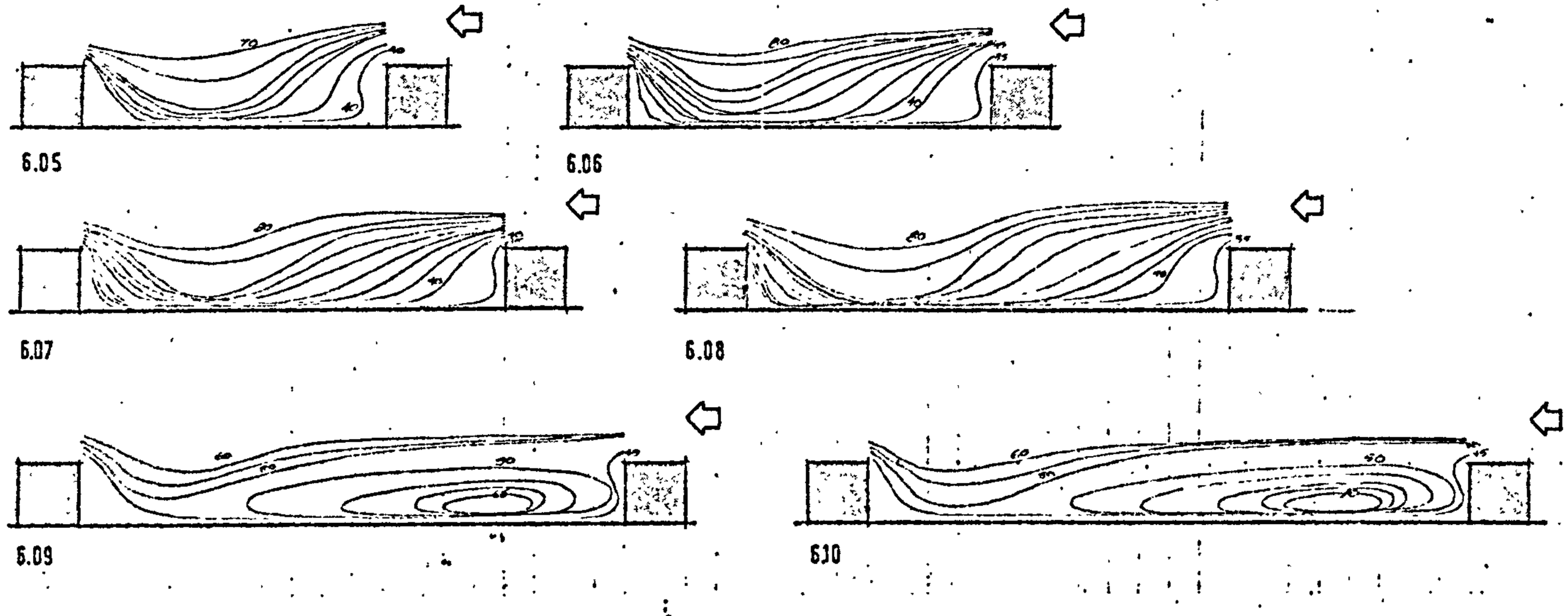


DIAGRAM 3.45: FLOW PATTERNS AT BLOCK LENGTH 6 ($\theta = 45°$)

The main effect of increase in block length in this case is the appearance of an upwind vortex at the larger spaces 9 and 10. This is also accompanied with the shift of the highest velocity zones for these two spaces from the downwind ends in the previous cases to an upwind position in this case.

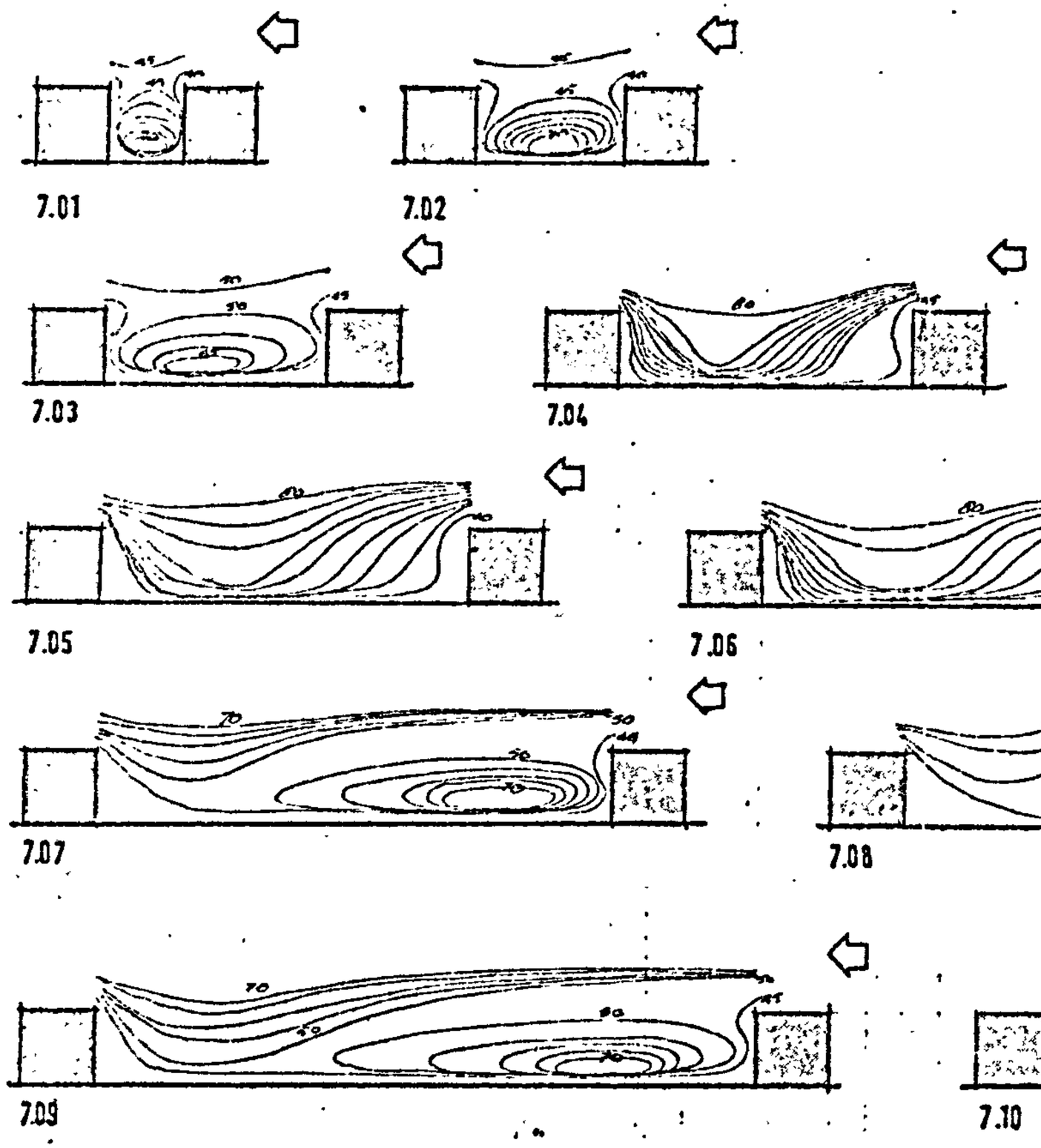
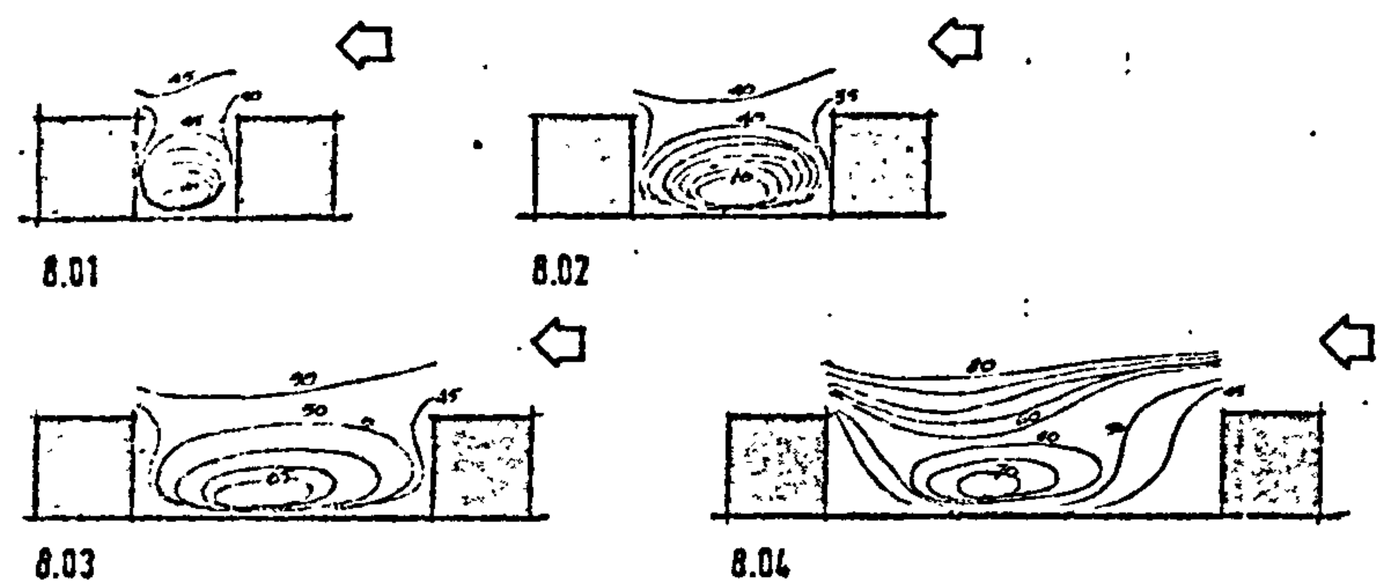


DIAGRAM 3.46: FLOW PATTERNS AT BLOCK LENGTH 7 (θ = 45°)

The upwind vortex becomes more frequent in this case for the larger spaces. All spaces 7,8,9 and 10 have an upwind vortex and their highest velocity regions locate nearer to the upwind end of the space. The space filling vortices still prevail in the smaller spaces 1,2 and 3. For the intermediate spaces as well as for the larger spaces (beyond the vortex) the flow dips towards the downwind end.



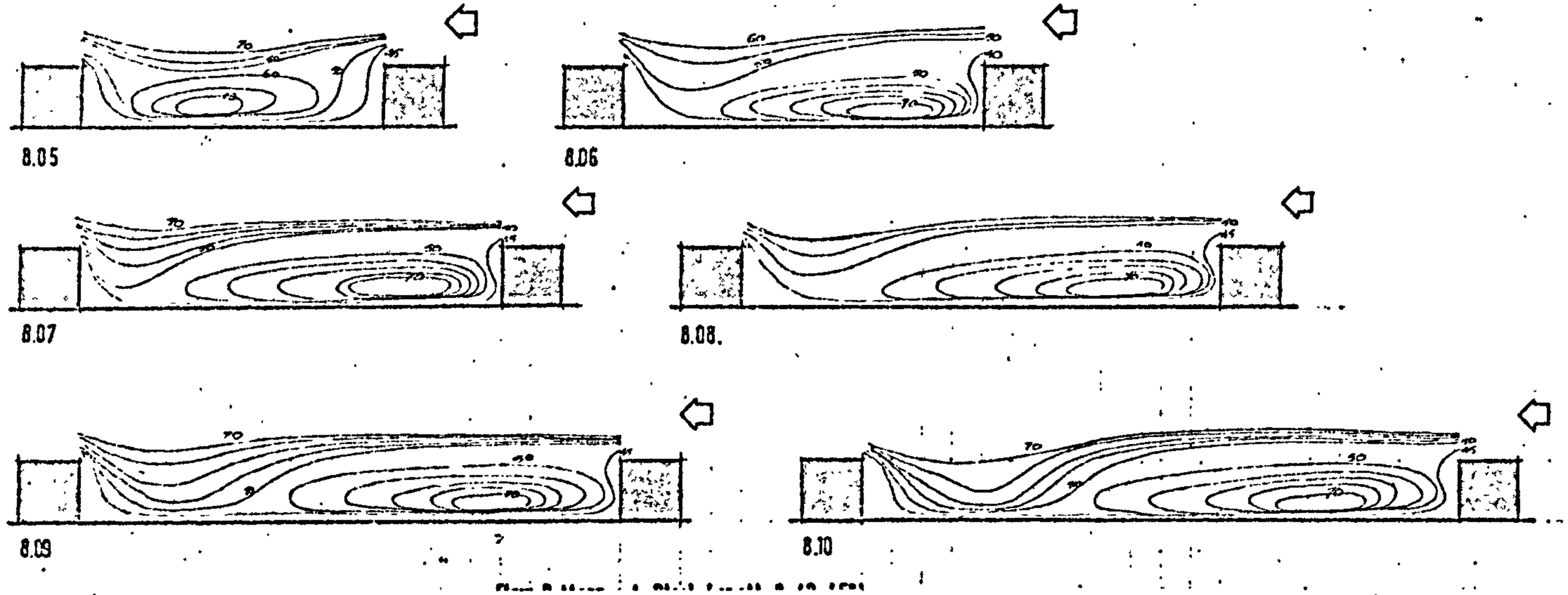


DIAGRAM 3.47: FLOW PATTERNS AT BLOCK LENGTH 8 (θ = 45°)

At this block length all space sizes show a vortex in their flow patterns. The vortices are either space filling as in spaces 1,2,3, centrally located within the space as in spaces 4 and 5 or locate in the upwind end as in spaces 6,7,8,9 and 10. The dip of the flow towards the upwind end is shown only in the case of spaces with upwind vortices.

The only change in the patterns concerning this arrangement is at spaces 4 and 5. For space 4 the vortex becomes larger. At space 5 the vortex shifts slightly from a central position in the previous case towards the upwind end of the space.

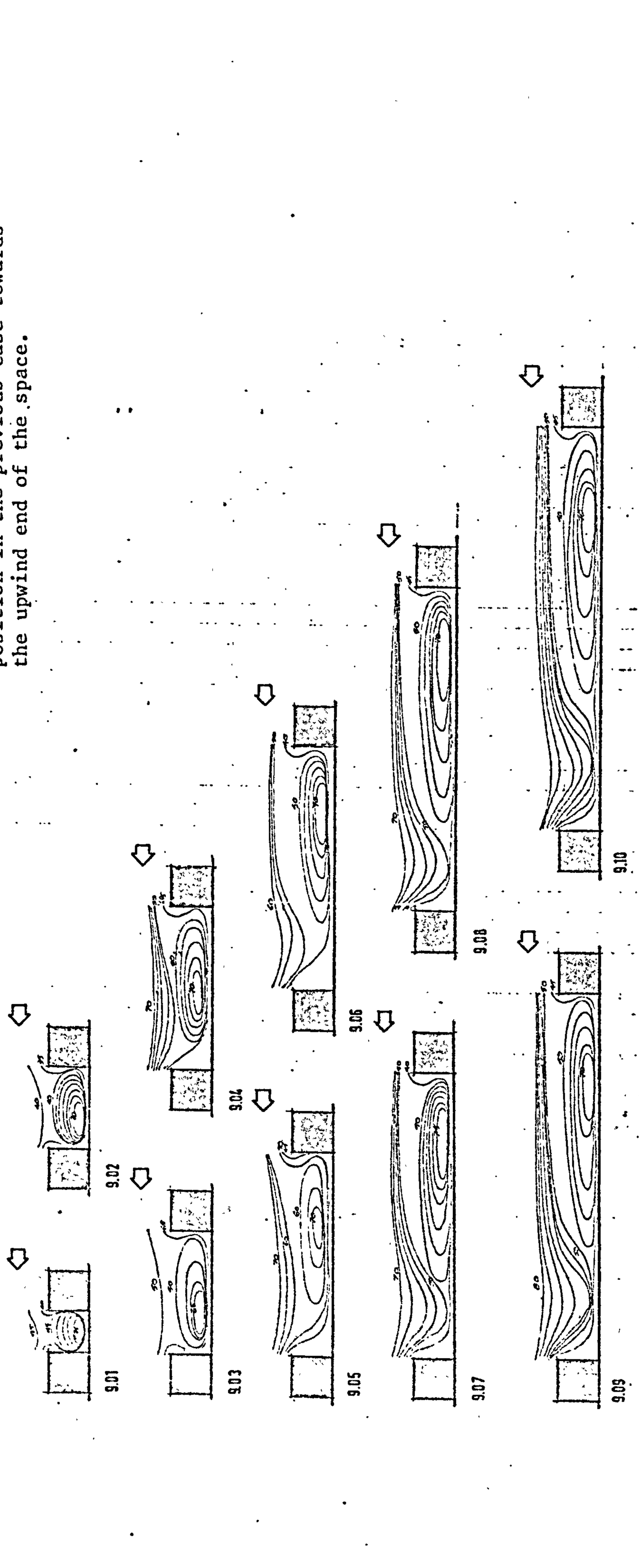


DIAGRAM 3.48: FLOW PATTERNS AT BLOCK LENGTH 9 ($\theta = 45°$)

At this block length and the next the patterns remain more or less similar to the previous case. The only changes concern the values of highest velocities and other speed contours.

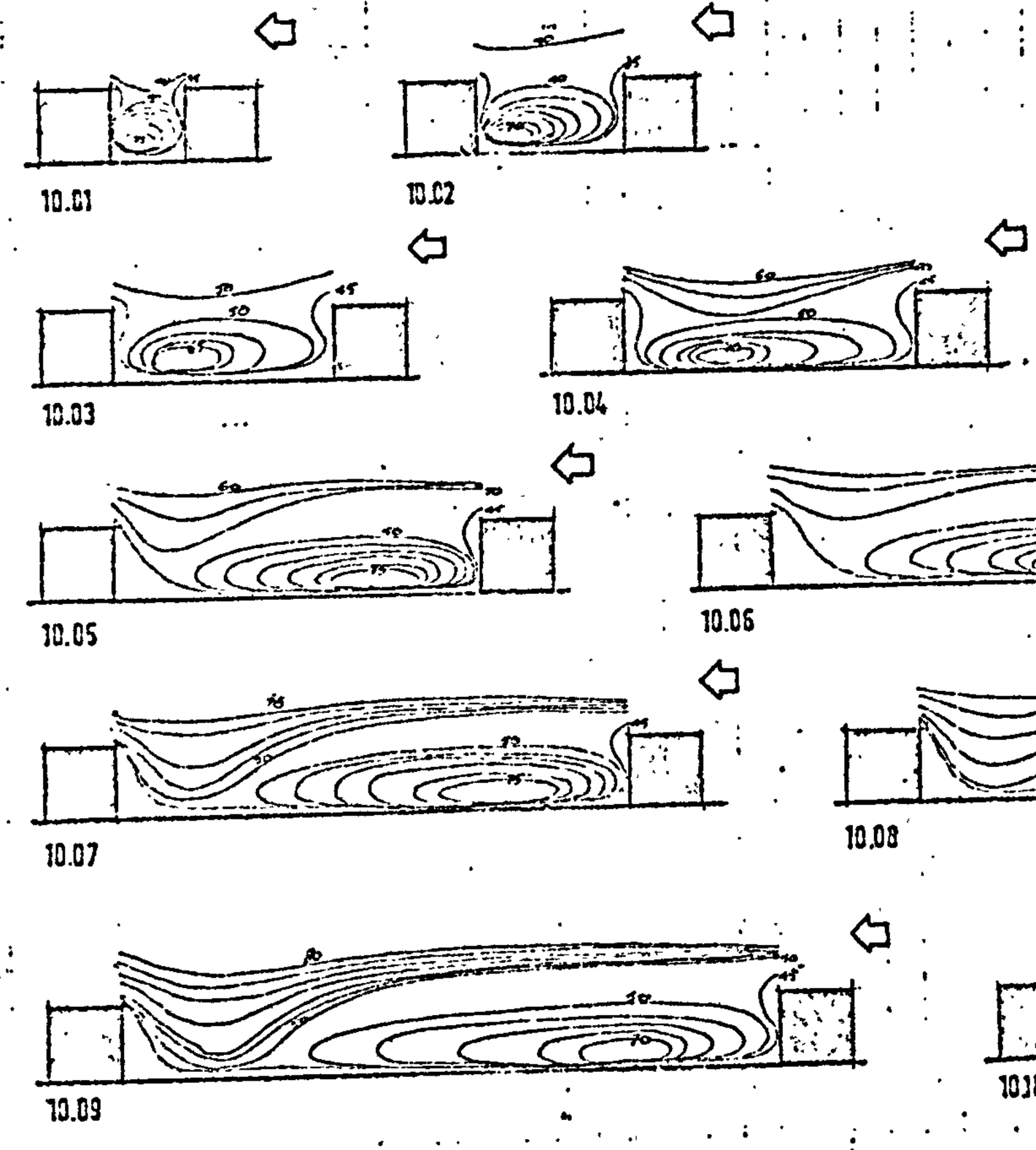


DIAGRAM 3.49: FLOW PATTERNS AT BLOCK LENGTH 10 ($\theta = 45°$)

See Diagram 3.49 for comment.

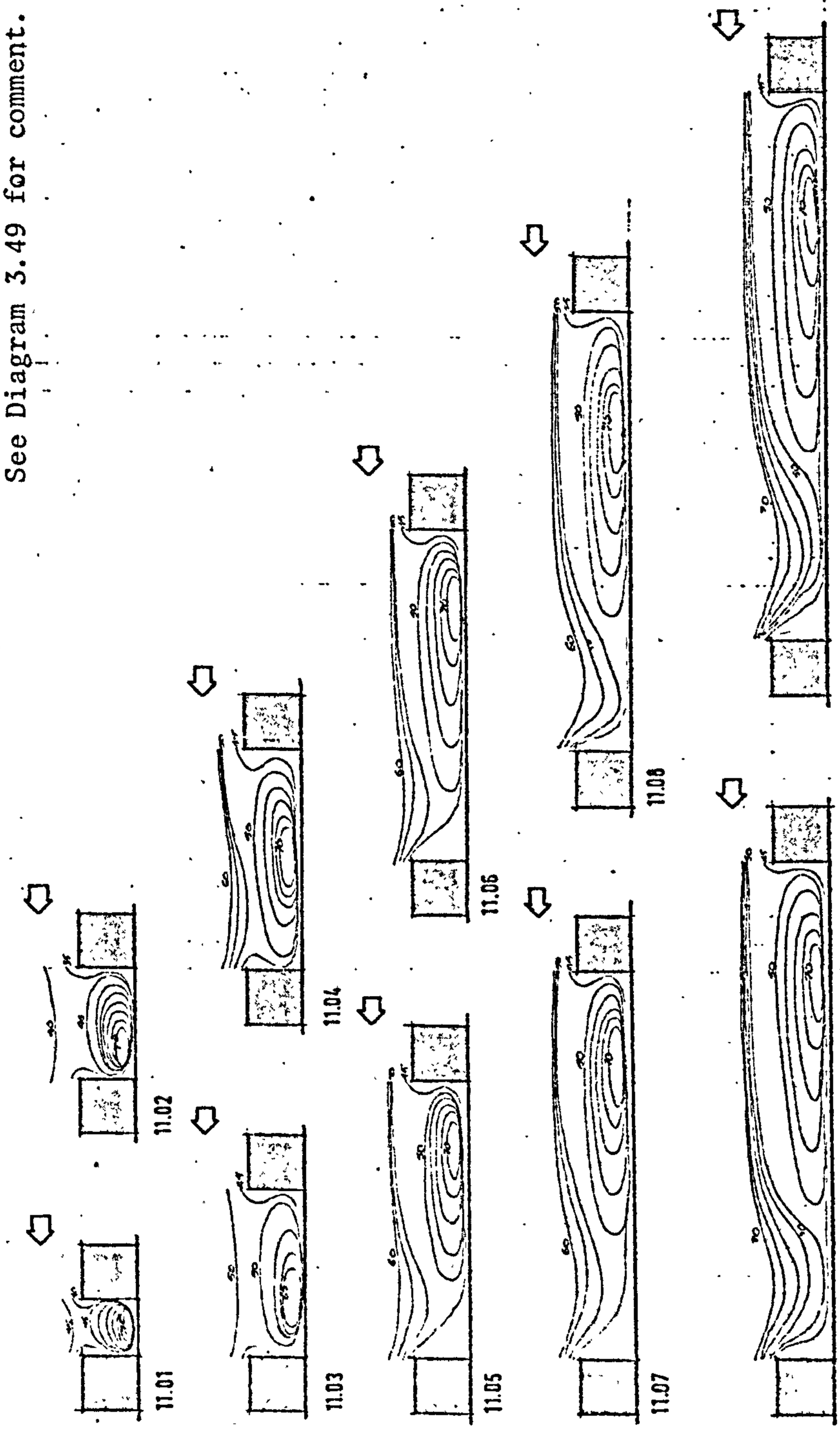


DIAGRAM 3.50: FLOW PATTERNS AT BLOCK LENGTH 11 ($\theta = 45°$)

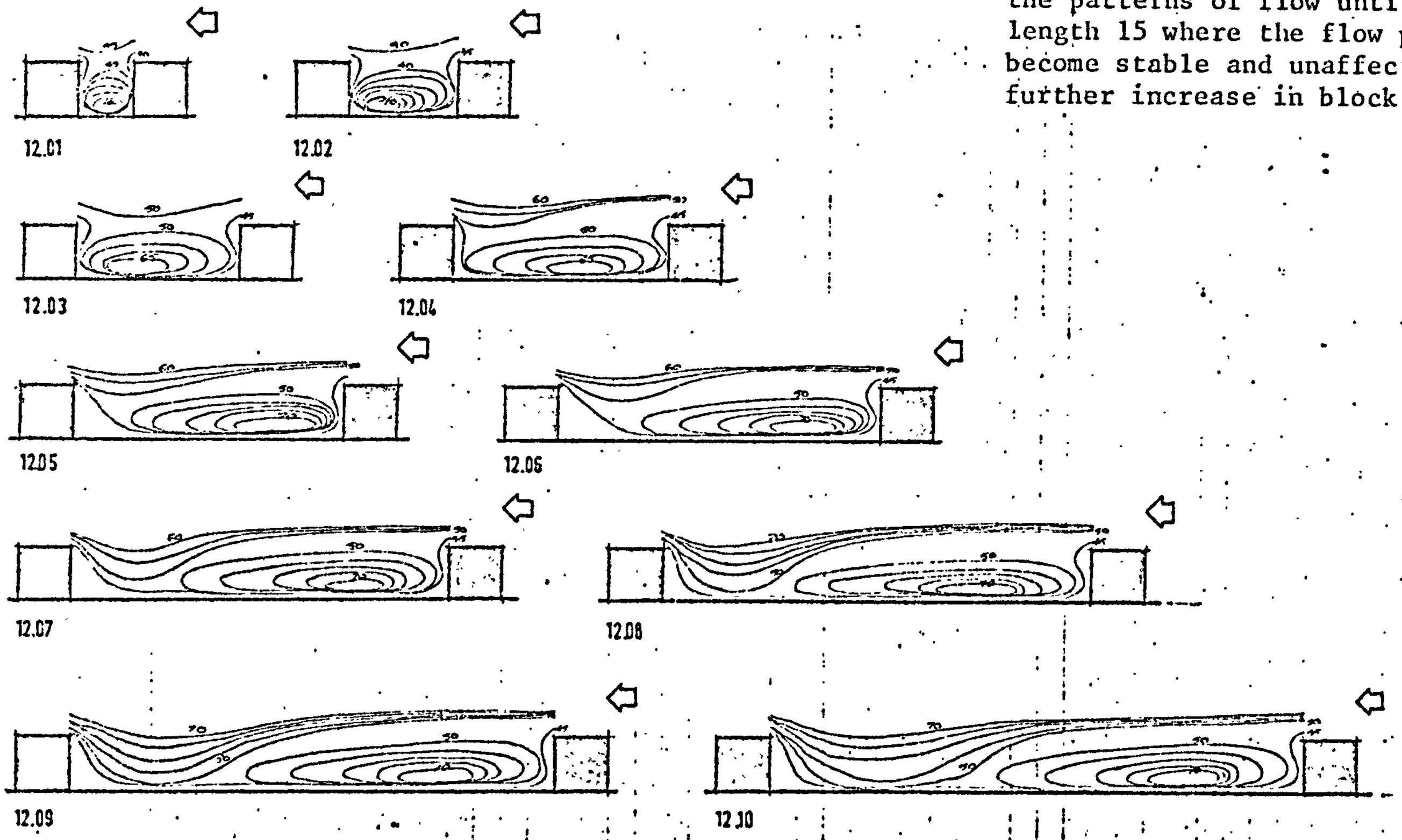


DIAGRAM 3.51: FLOW PATTERNS AT BLOCK LENGTH 12 ($\theta = 45°$)

The main change here apart from the values of highest velocities is the diminution in the sizes of the vortices at spaces 9 and 10. This continues to be the main change in the patterns of flow until block length 15 where the flow patterns become stable and unaffected by further increase in block length.

See Diagram 3.51 for comment.

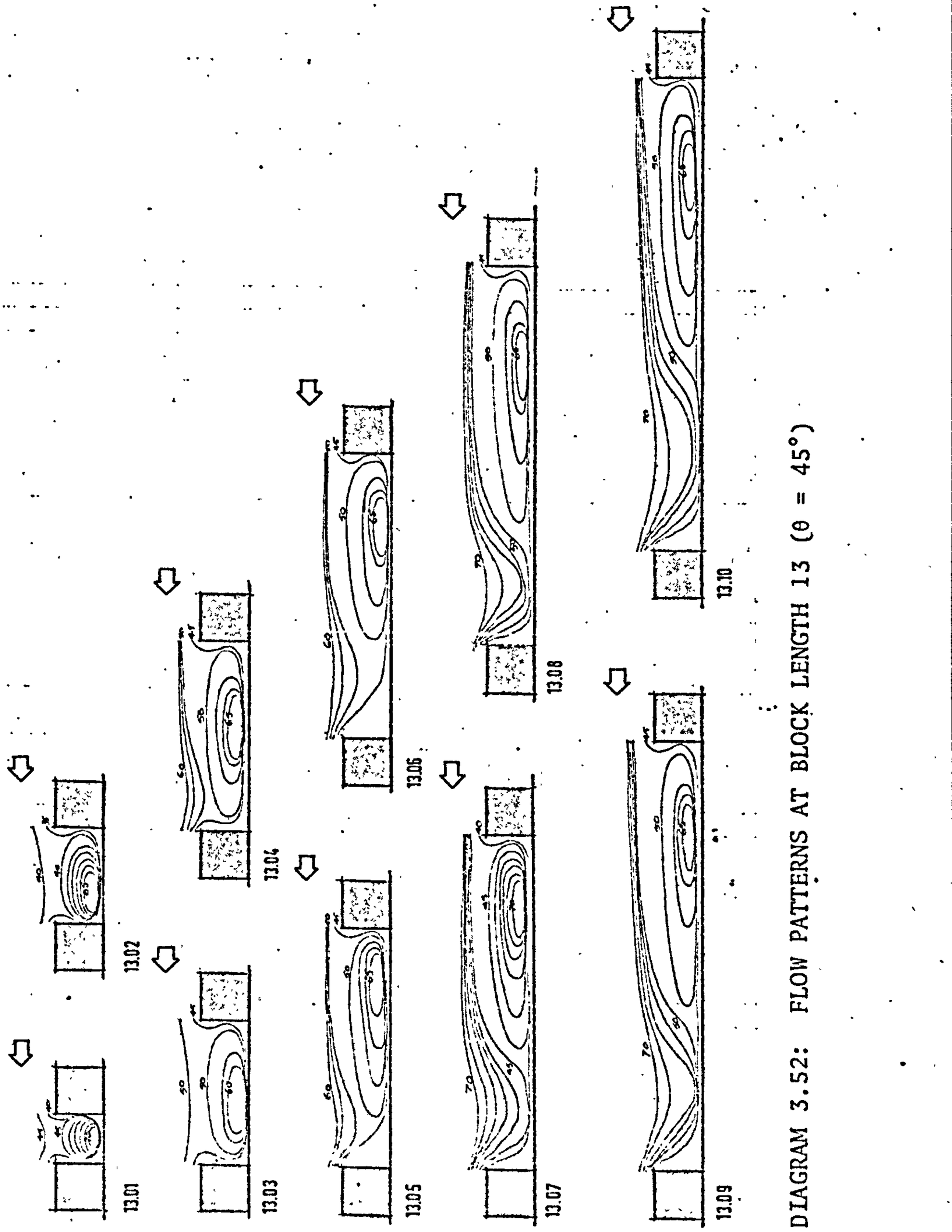


DIAGRAM 3.52: FLOW PATTERNS AT BLOCK LENGTH 13 (θ = 45°)

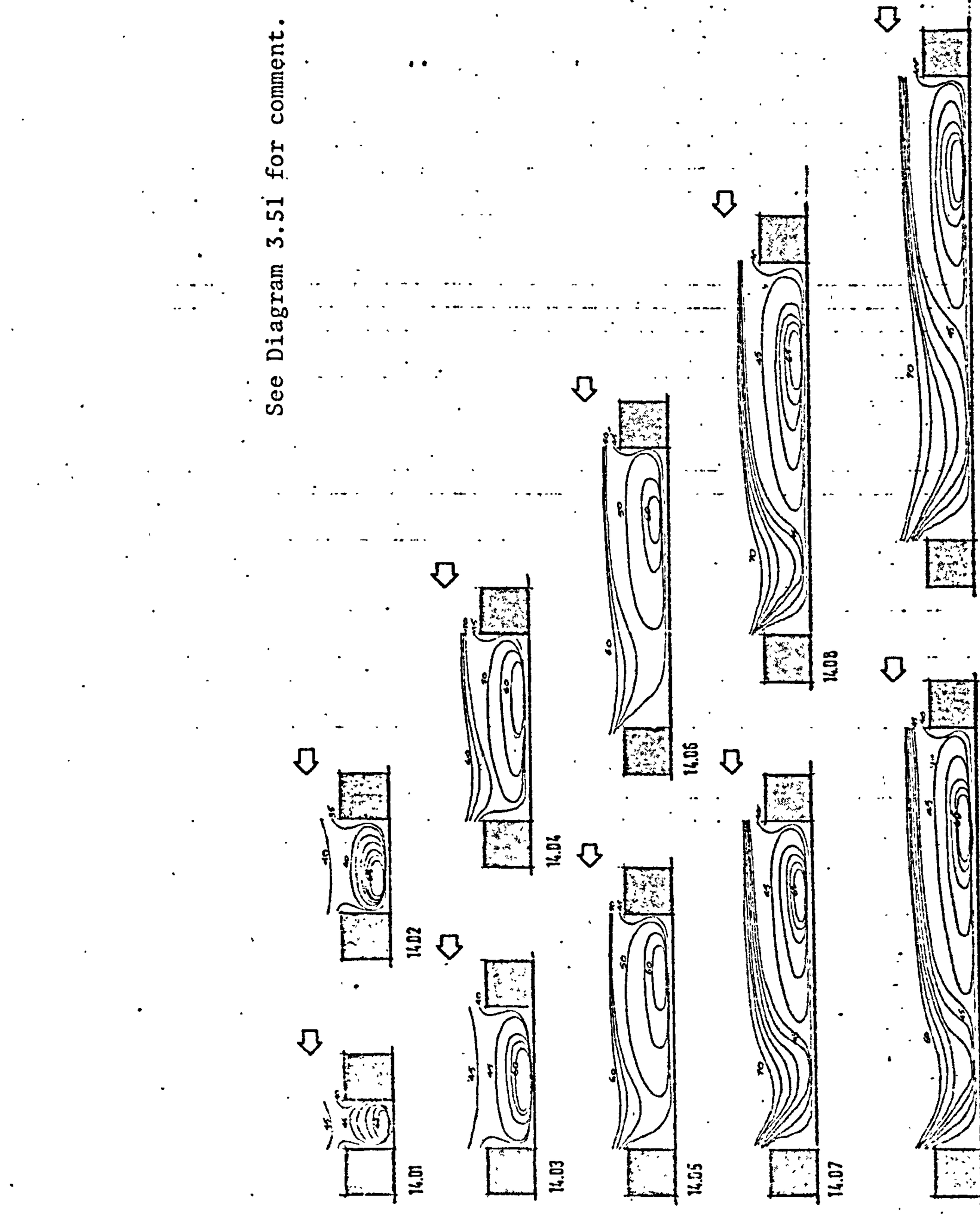


DIAGRAM 3.53: FLOW PATTERNS AT BLOCK LENGTH 14 ($\theta = 45°$)

See Diagram 3.51 for comment.

See Diagram 3.51 for comment.

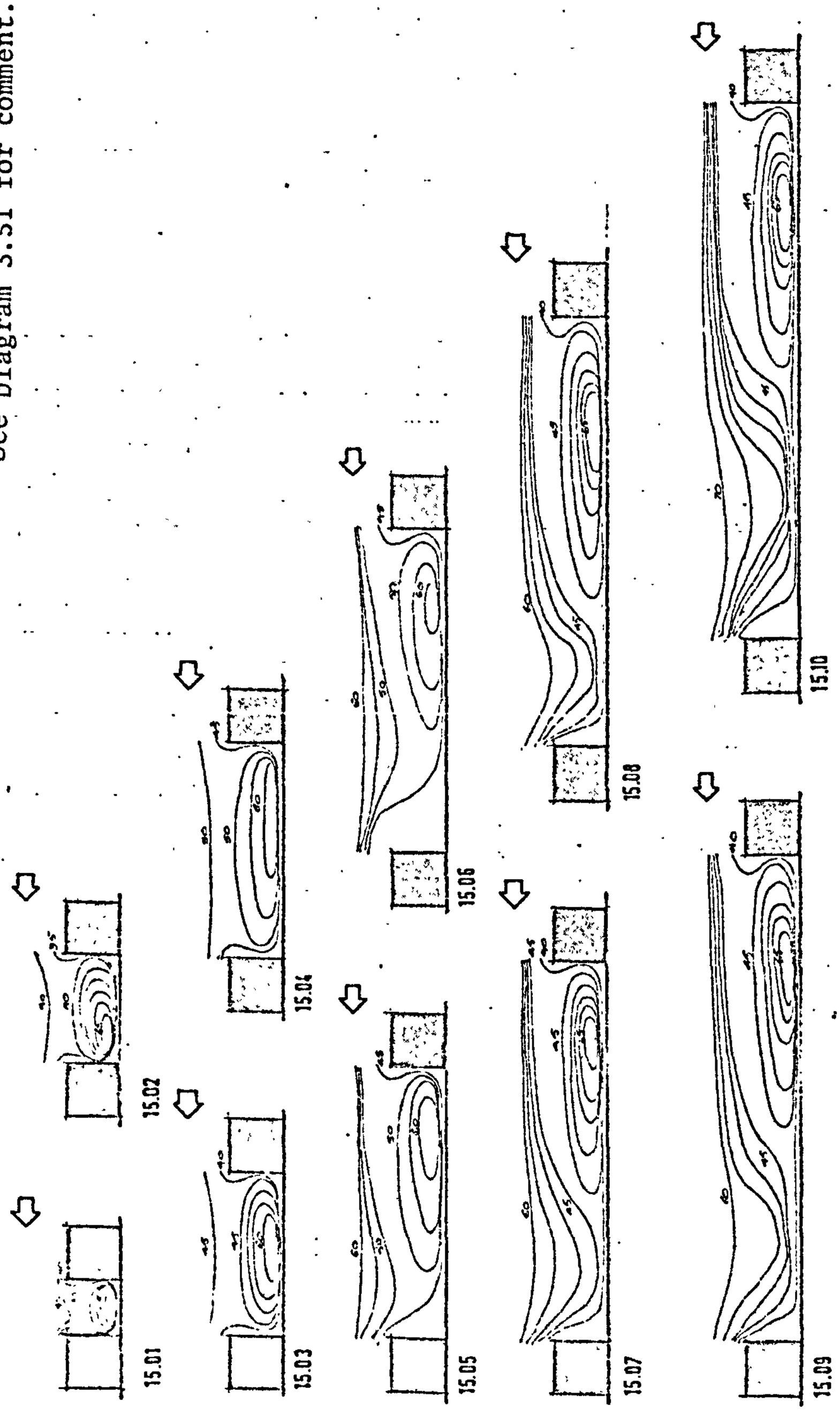


DIAGRAM 3.54: FLOW PATTERNS AT BLOCK LENGTH 15 ($\theta = 45°$)

C H A P T E R I V

THE DEVELOPMENT OF A MEASURE OF EXPOSURE

1.00 INTRODUCTION

1.01 One of the most important measures of wind flow in a specific part of a built form (enclosed or outdoor space) defines its relative exposure or shelter characteristics. This will be termed the exposure measure. An exposure index is a numerical value of the exposure measure and is a property of any given form revealing an aspect of wind conditions in it. The designer's need for evaluating and comparing alternative forms from the environmental wind point of view calls for measures of exposure that are relatively simple, economic, reliable and capable of differentiating between forms by being sensitive to changes in relevant form aspects. To arrive at a measure or measures of such properties is the objective of this chapter. The data for this and the coming chapters is the same as that used for the construction of the speed contours in chapter III. Later on, however, larger samples of measurements are taken for further tests on the exposure measures. The notation used for this and the next chapter is shown in diagram 4.1.

PROPERTIES OF THE MEASURES OF EXPOSURE

2.01 The designation of a uniform grid to sample speed measurements in a given space is the most practical guide to scan the speed distribution in the space. In choosing a uniform grid density for the measurements sample there is an implicit assumption that the different regions constituting the measurements plane have identical flow conditions. One implication of this is that the change in speeds from one point to that subsequently after or before it has the same gradient, no matter where these points lie within the space. It is reasonable to assume that this is not the case and that the speed gradient between points

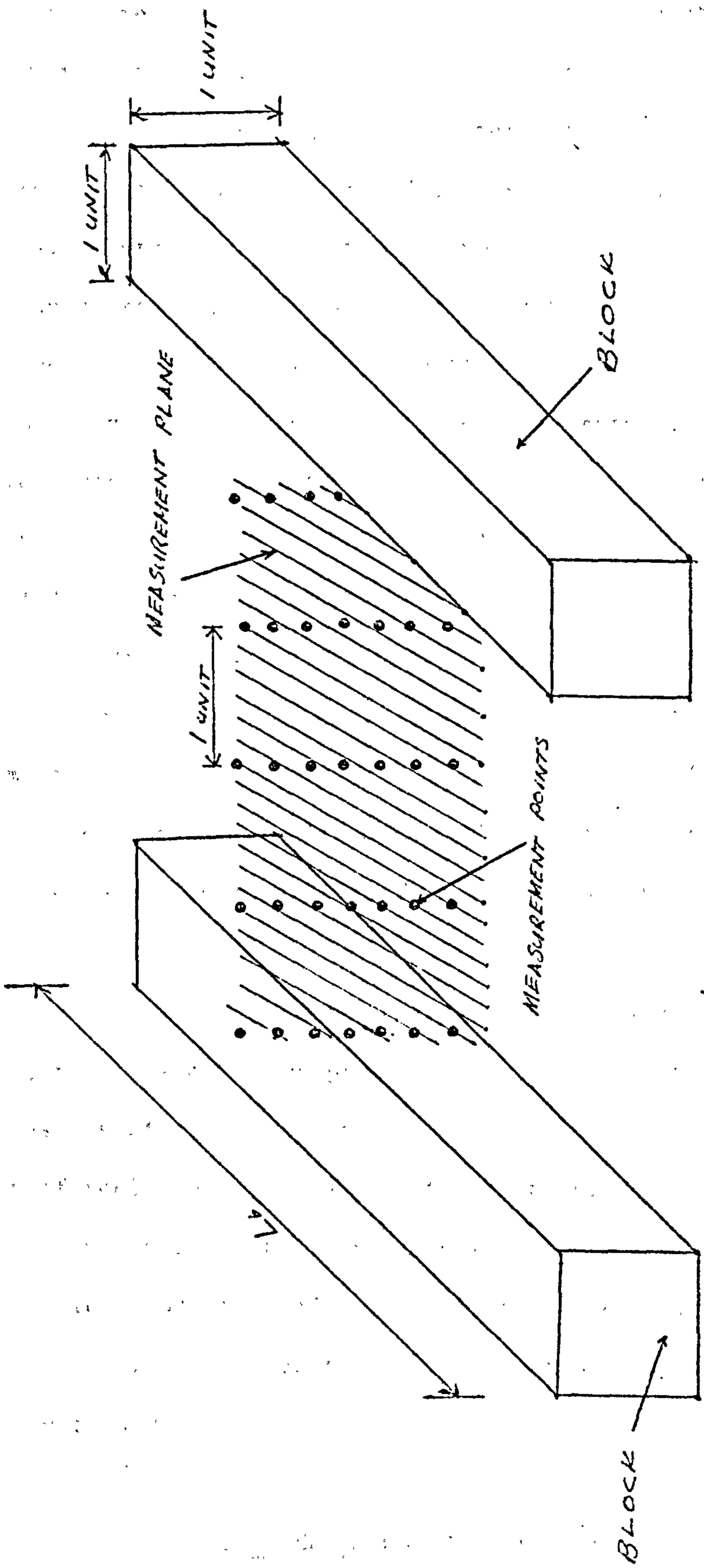


DIAGRAM 4.1: MODEL ARRANGEMENTS, NOTATION AND MEASUREMENT PLANE

within a given region of the space depends on the relative position of the region within the space. This implies that the statistical concept of an average measure of exposure associated with a uniform density grid of measurements is rather unreliable and that such exposure measures are likely to have a strong local bias in favour of the regions and form arrangements where speed gradients are relatively gentle. To overcome this bias there are three possible approaches:

a) to increase the density of the measurements grid throughout.

b) to increase the density of the grid where the rates of change in speeds with space are likely to be high. This will involve at least two sets of measurements: an initial set to determine where the high speed gradients occur and a second set taken over a differential grid density guided by the initial set of measurements.

c) to devise theoretically more sophisticated statistical measures of exposure capable of dealing with differential change patterns.

2.02 Approaches (a) and (b) are likely to be uneconomic and time consuming considering the present techniques of measurement. Theoretically sophisticated measures of exposure are likely to be less usable and less popular on account of their relative complexity. It is, therefore, a reasonable objective in the search for an exposure measure to look for one or ones that are simple, economic, and relatively reliable in their exposure estimations. This is the objective of the experimental program undertaken and discussed in this chapter.

THE MEASURES OF EXPOSURE

3.00 Seven different measures of exposure are given below. They are dif-

ferent in formulation and in their data needs.

3.01 Exposure Measure I_o:

$$I_o = \left[\sqrt{\frac{\sum_1^N V_i^2}{N}}\right] \Big/ 100$$

where V_i is the speed at a point expressed as a percentage of free flow (chapter III)

N is the number of points at which velocity measurements are taken.

The values and behaviour of I_o are almost similar to I_1. Therefore, it is only stated here.

3.02 Exposure Measure I_1:

$$I_1 = \left[\sum_1^N V_i\right] \Big/ 100N$$

where N is the number of points at which velocity readings are taken.

V_i is the speed at point i (expressed as a percentage of free flow reading).

A slightly different version of this measure was used in air movement studies by Givoni.[73] Based on the statistical arithmetic average, it is the simplest measure of exposure. It takes values from 0 to 1 where 1 is the reference exposure (in this case, the free flow reading taken before the models were put at a height equal to twice that of the model's).

3.03 Exposure Measure I_2:

$$I_2 = \frac{C}{100}$$

where C is the value of the geometric centre of the data arranged in order of magnitude. Dividing by 100 adjusts the index value to values ranging between 0 and 1.

This measure of exposure is based on the value of, or the average value of, the middle values of the velocity readings arranged in order of magnitude. Like the arithmetic average, it is a measure of central tendency. It differs from I_1 and I_o in that it requires basic data to be arranged in order of magnitude and the value of the geometric centre of the arrangement taken. Further, it takes no account of the number of measurements in determining the central value.

3.04 Exposure Measure I_3:

$$I_3 = \left[\sum_{i=1}^{10} n_i \; V_i\right] \Big/ 100N$$

where n_i is the number of measurements falling within the velocity interval i.

V_i is the velocity representative of the measurement class (taken at intervals of 10 starting at 5%)

N is the total number of measurements for all classes.

This measure of exposure is based on the summation of the relative frequencies of the data multiplied by a representative velocity for each group. In formulating it, velocity measurements are grouped in classes at 10% intervals.

3.05 Exposure Measure I_4, diagram 4.2 :

$$I_4 = \left[\sum_{i=0}^{100} V_i \; a_i\right] \Big/ 100A$$

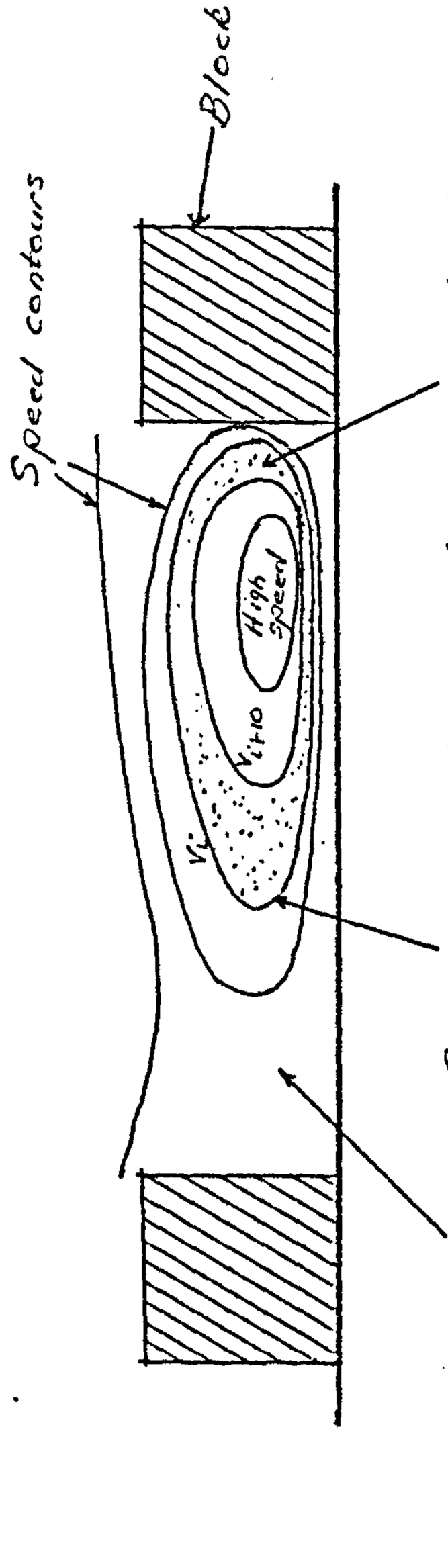


DIAGRAM 4.2: EXPLANATION OF THE PARAMETERS OF THE EXPOSURE MEASURE

where V_i is the lower value of two speed contours bounding the area a_i.

a_i is the area for which local exposure index is computed.

A is the total area of the measurement plane for which an exposure index is to be computed.

This is the first measure which utilises an areal data base (para. 4.01 below). It is founded on a relative average concept. The plane for which an exposure index is to be computed is divided into sub-areas by the speed contours. For any such area, expressed as a proportion of the total plane area, a local exposure index is computed by multiplying by V_i. The value of the exposure index for the whole area of the measurement plane is the sum of the local area indices.

3.06 Exposure Measure I_5, diagram 4.3:

$$I_5 = \sum_{i=0}^{100} \left[\frac{a_i (V_i + V_{i+10})}{2} \right] / 100A$$

where V_i, V_{i+10} are velocities represented by the speed contours at 10% intervals.

a_i is the area bounded by the two speed contours V_i, V_{i+10}

A is the total area for which the exposure index is to be computed.

This measure is essentially similar to I_4 in that it calculates first local exposure indices for areas defined by the speed contours and sums them over the area for which the exposure index is computed. It is different, however, in that the speed is taken as an average of the values of the two speed contours bounding the area.

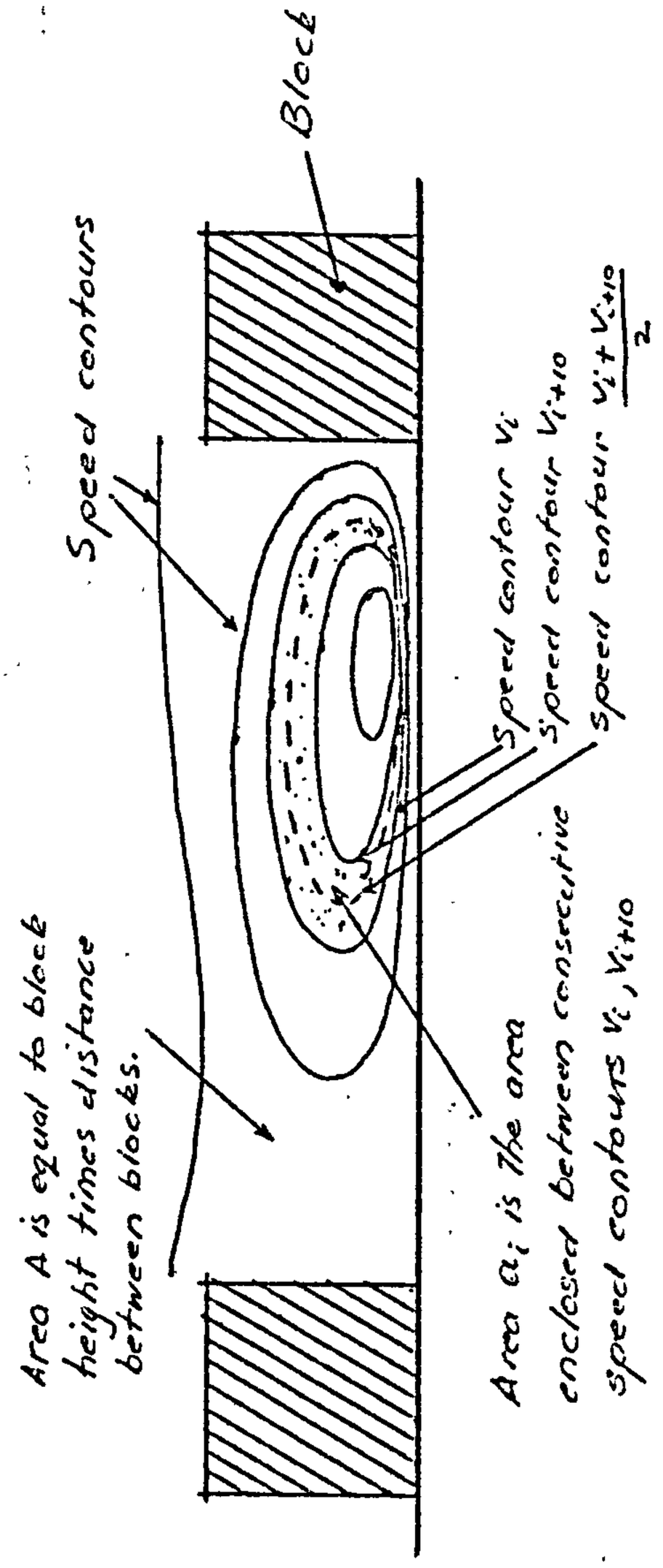


DIAGRAM 4.3: EXPLANATION OF THE PARAMETERS OF THE EXPOSURE MEASURE I_5

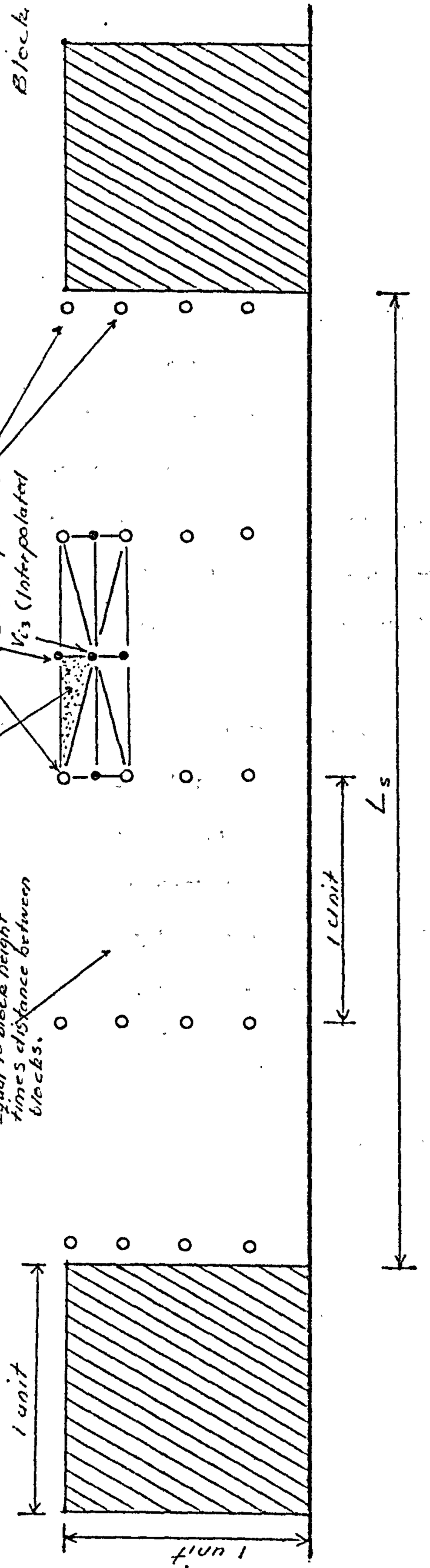


FIGURE I_6

PARAMETERS OF THE EXPOSURE MEASURE

FIGURE 4.4: EXPLANATION OF THE DIAGRAM

3.07 Exposure Measure I_6, diagram 4.4:

$$I_6 = \sum_{i=1}^{N} \left[\frac{a_i \ (V_{i_1} + V_{i_2} + V_{i_3})}{3} \right] \Big/ 100A$$

where a_i is a triangular area generated by joining sets of four points of grid units vertically, horizontally and diagonally (diagram 4.4).

V_{i_1}, V_{i_2}, V_{i_3} are the velocity values at the vertices of the triangular areas.

N is the total number of triangular areas.

A is the total area of the measurement plane for which the exposure index is to be computed.

This measure also comprises an areal component and locally averaged measurements. The rectangles formed by sets of four points in the initial grid (see para.1) are divided into triangular units as shown in diagram 4.4. The numbers at the vertices of the triangles (other than those at the corners of the rectangles) are interpolated speed values. Each triangular area has an exposure value defined by the area itself relative to the total plane area and the arithmetic average of the velocity values at the vertices.

The exposure of the plane is the sum of the relative exposure indices of the triangular areas.

THE CHOICE OF AN APPROPRIATE MEASURE OF EXPOSURE

4.01 Although the seven measures of exposure are different in formulation, yet they have a common property as measures of averages. They can be divided into two main groups according to the type of data they require

in computing an exposure index. These are:

a) A group that uses the experimental measurements directly as they occur at the measurement points of the grid. These can be termed point-based measures of exposure. They comprise I_0, I_1, I_2 and I_3.

b) A group that requires the grid measurements to:

1. be transformed into speed contours,
2. average speed contours over appropriate areas,

and, as a result of 1 and 2

3. increase the effective size of measurements sample.

This group can be termed area-base measures of exposure. It comprises measures I_4, I_5 and I_6.

4.02 Because of the differences between the measures in formulation and data structure, it is important to establish

a) to what extent the formulation of the measures affects the differences in the value of the exposure indices.

b) whether the data structure produces different values of the exposure index computed by different measures for the same arrangement and how different.

c) whether the size of the measurements sample used as a basis of point-based and area-based data structures has a significant effect on the exposure index estimations of the measures.

d) whether the different measures show different degrees of sensitivity to progressive changes in form parameters.

4.03 The existence of significant differences between the measures as a result of differences in their formulations, data structures, size of sample of measurements and sensitivity to change in form parameters would

make it imperative to choose an appropriate measure of exposure. To decide whether the differences are significant can only be arbitrary. But, as the results of the computation will show, these differences range between 9% and 21% of the maximum exposure value (the free flow value) of 100% existing in all arrangements. These differences in estimation of the exposure index values are considered high enough to justify the search for and the choice of an appropriate measure of exposure. The appropriate measure, or measures, of exposure will be chosen from among the seven measures according to the criteria that:

a) it should show little or no response to the size of measurement samples. This is investigated by taking samples larger than the initial one and comparing the different indices resulting from each sample.

b) it should show little or no change in the exposure index value as a result of differences in data structure.

c) it should utilize minimum measurements samples.

d) it should show relatively high sensitivity to changes in form. This aspect is judged by the statistical range of values of the exposure indices pertinent to the range of values which the relevant form aspect takes.

4.04 In summary, we can specify as an appropriate and a reliable measure of exposure as that which utilizes minimum measurement samples, shows little or no change in index value with larger samples, independent of data structure and relatively sensitive to changes in form. Since there is no way of knowing the 'right' exposure value the measure which satisfies conditions a, b, c and d will be taken as the appropriate measure of exposure. In this respect I_5 and I_6 are found to be the most appropriate measures. For this reason I_5 is taken as the standard against which the

behaviour of the other measures is compared (see section 13).

RESULTS OF COMPUTATIONS OF EXPOSURE INDICES FROM EXPERIMENTAL DATA USING DIFFERENT MEASURES OF EXPOSURE

5.00 Exposure Measure I_1:

5.01
$$I_1 = \frac{\sum_{i=1}^{N} V_i}{100N}$$

5.02 The values of the exposure indices computed from I_1 for normal orientation and an array of 20 block lengths (L_b) is shown graphically in diagram 4.6. Diagram 4.5 shows the relationship between I_1 and space size (L_s).

5.03 Diagram 4.5 shows that the effect of increasing the space size on exposure index is closely associated with change in block length. At shorter block lengths it shows an increase in the value of the exposure index which decreases with the increase in space sizes between longer units. At block length 1 there is a gentle increase in I_1 between values 1 and 4 of L_s, and a rapid increase after that. At this block length the lowest and highest values of the whole range of arrangements occur: the lowest at space 1 and the highest at space size 10 (0.47 - 0.77).

5.04 Increasing the block length to 2 increases the value of I_1 to 0.53 at space 1. This value drops to about 0.50 at space 3 and starts to increase, first slowly, but relatively rapidly after space 4, to reach its highest value, 0.69, at space 10. Between spaces 1 and 4 the values of I_1 are less for block length 1 than those for block length 2. For spaces greater than 4 this is reversed and at space 4 the values of I_1 for the two block lengths coincide.

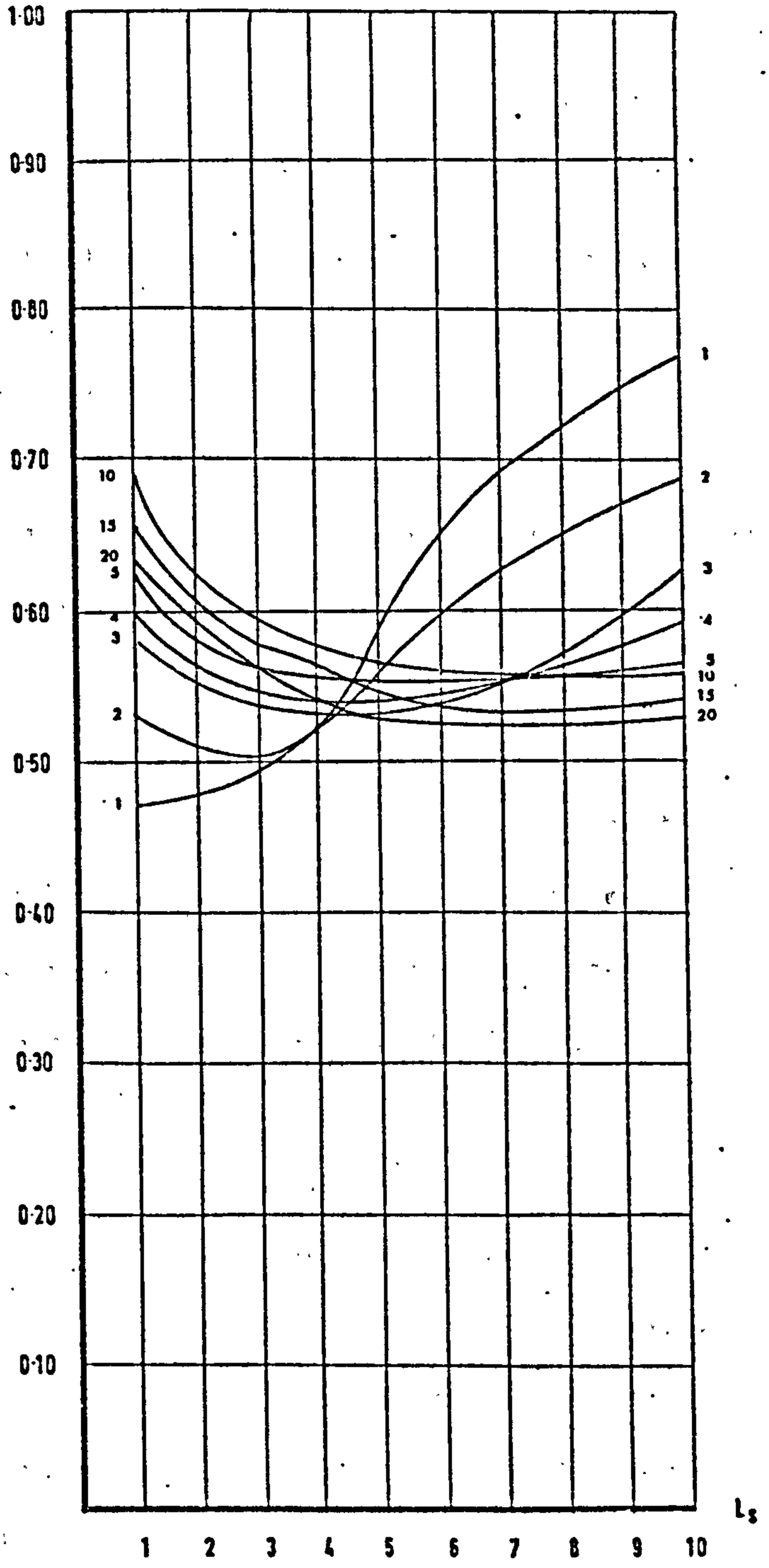


DIAGRAM 4.5 RELATION BETWEEN EXPOSURE MEASURE I_1 AND SPACE SIZE L_s (FOR DIFFERENT BLOCK LENGTHS)

5.05 At block length 3 the value of I_1 drops between spaces 1 and 4. It remains stationary at the value 0.53 before it starts to increase at space 6 to reach its highest value, 0.62, at space 10. At about space 4 I_1 for this block length is approximately the same as those for block lengths 1 and 2. The behaviour of I_1 for this block length differs from the previous two in that its minimum value occurs at relatively larger space sizes, 4-6, with a relatively low range between maximum and minimum values.

5.06 The values of I_1 at block length 4 follow the same pattern as those of block length 3, only higher. At space 7 they coincide. For spaces greater than 7 the I_1 values for this block length become lower than those of block length 3. The highest value of I_1 here is 0.60 occurring at space size 1 and the lowest is 0.54 occurring at the range of spaces 3 - 6. Contrary to its behaviour at block lengths 1, 2 and 3, I_1 takes its maximum value at the shortest space size. Further increases in block length show more of this tendency.

5.07 At block length 5 the values of the exposure index decrease with increase in space size. From a maximum of 0.62 at space 1, I_1 decreases to a mimimum value of 0.55 which remains stationary between space sizes 4 - 7. Towards space 10 there is a slight increase. The values of I_1 for this block length coincide with those of block length 1 at about space 4 and with those of block length 2 at space 5, and at space 7.5 for block lengths 3 and 4. For small space sizes and until space 7.5 the values of I_1 are higher for block length 5 than those of block length 4. This relationship is reversed beyond space size 7.5.

5.08 Between block lengths 5 and 10 the value of I_1 begins to fall in relation to previous block lengths. The difference in values of I_1 between successive block lengths in this range decreases towards space size 10. This is shown by looking at the values of I_1 at block length 10. At space 1 the value of I_1 is maximum at 0.69. It decreases steadily to a minimum value of 0.56 at space 6. This is also the index value where it coincides with block length 5 at space 8. At space 1 the difference in the index value between block lengths 5 and 10 is 0.07 but at space 8 it is 0 and at space 10 the difference is negligible. This shows that the change in block length in the range 5 - 10 has a more appreciable influence on the values of I_1 at smaller space sizes.

5.09 A further increase of the block length from 10 to 15 yields a lower set of I_1 values. This is reduced even more when the block lengths increase to 20. The behaviour of I_1 with the increase in space size in this range is similar to that at block length 10: taking maximum values at small space sizes, lowest values at about space sizes 4 - 6 with only slight increase towards the larger space sizes.

5.10 Diagram 4.6 shows the relationship between the exposure measure I_1 and block length L_b, for the range of 10 space sizes. For space size 1 the increase in block length increases the value of I_1 from a minimum value of 0.47 at block length 1 to a maximum value of 0.69 at block length 10. After that it decreases gradually to reach 0.63 at block length 20. For space size 2 the minimum value of I_1, 0.48, also occurs at block length 1 and it increases with increase in block length. This increase, however, is not as rapid as in the previous case. It reaches a lower maximum value, 0.62, at block length 10 and remains at this value until block length 20. The difference between the values of I_1 for spaces 1

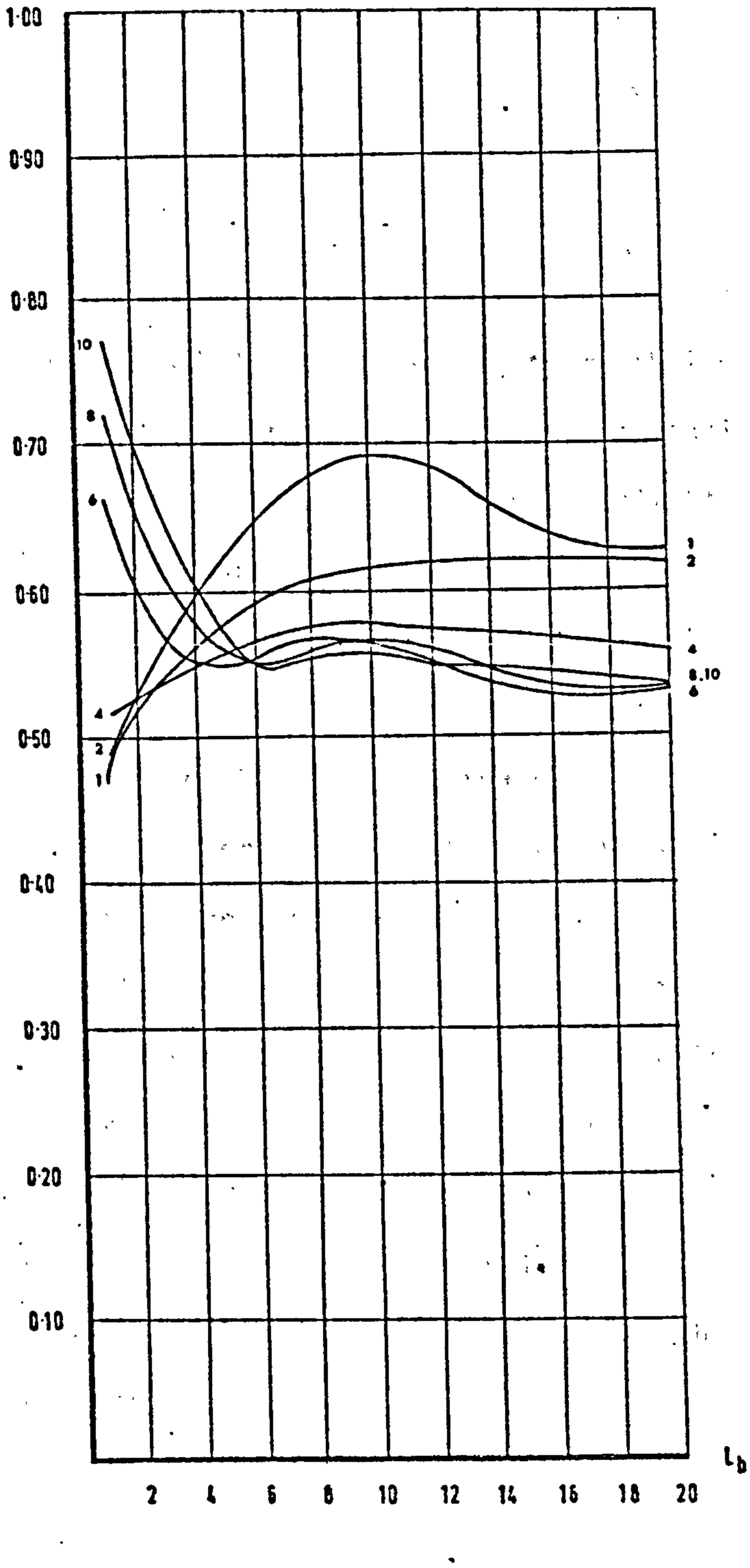


DIAGRAM 4.6 RELATION BETWEEN EXPOSURE MEASURE I_1 AND BLOCK LENGTH L_b (FOR DIFFERENT SPACE SIZES).

and 2 are highest at block lengths 9 - 11, but decrease towards block length 10 and remains at this value until block length 20. The difference between the values of I_1 for spaces 1 and 2 are highest at block lengths 9 - 11, but decrease towards block lengths larger and smaller than this range.

5.11 At space size 4 the value of I_1 is higher than previously at block length 1. An increase in block length causes I_1 to reach its maximum value for this spacing at block length 7 and it remains stationary until 11. Further increases in block length causes only a slight decrease in I_1. As in the previous cases, the maximum value occurs at block length 1 but the range of maximum and minimum values is much lower in this case.

5.12 Space sizes between 5 and 10 show a decrease in I_1 with increase in block length from 1 to 6. After block length 6 there is a slight increase in I_1 before reaching the minimum values at block length 20. The differences in values of I_1 for space sizes 6 - 10 are greatest at block length 1 diminishing with increase in block length. The largest drop in the values of I_1 occur between block lengths 1 - 6: from 0.66 to 0.55 for space size 6, from 0.72 to 0.55 at space 8 and from 0.77 to 0.55 in the case of space 10. At block length 6 the values of I_1 for spaces 6, 8,and 10 coincide;and with further increase in block length the differences in I_1 values are very small.

6.00 Exposure Measure I_2:

6.01
$$I_2 = \frac{C}{100}$$

6.02 Diagram 4.7 shows the relationship between I_2 and space size for the range of 20 block lengths. The minimum and the maximum values of I_2 appear at block length 1. At space 1 the value of I_2 is minimum for

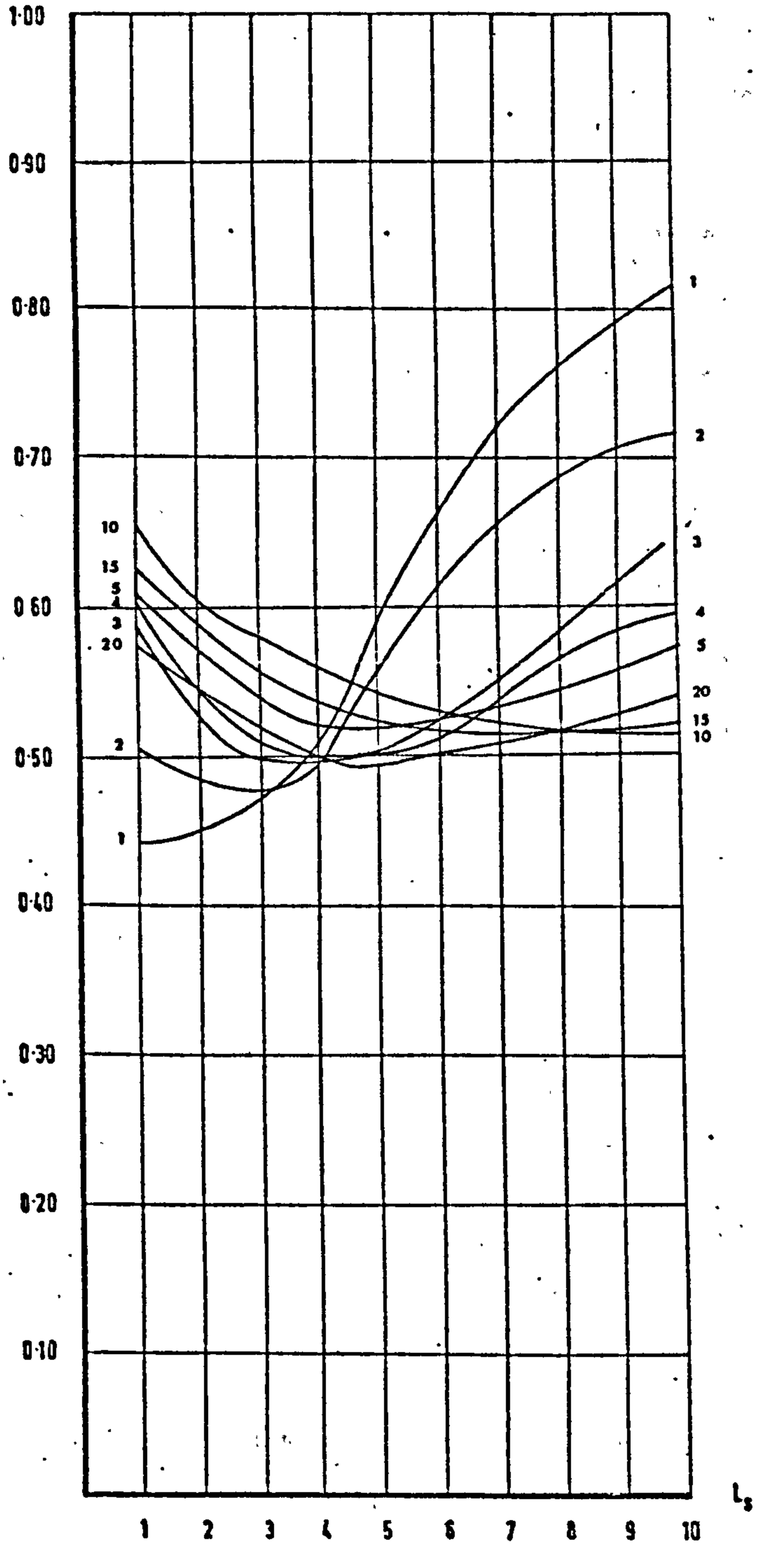


DIAGRAM 4.7 RELATION BETWEEN EXPOSURE MEASURE I_2 AND SPACE SIZE L_s (FOR DIFFERENT BLOCK LENGTHS)

block length 1, 0.44, and the maximum value is 0.82 at space size 10. The increase in the value of I_2 with increase in space size at this block length is gentle at the beginning. It increases after space size 3, but slows again at space size 8 with further space size increase.

6.03 Block length 2 shows an initial decrease in the value of I_2 with increase in space size. I_2 drops from 0.52 at space size 1 to a minimum of 0.47 at space 3. It increases again to reach a maximum value of 0.72 at space 10. The increase is relatively rapid between space 4 and 8 and it becomes gentle towards space 10. Between spaces 1 and 3 the values of I_2 are higher for block length 2, but coincide with those of block length 1 at space 3. Further increase in space increases the difference in I_2 values for block length 1 and 2 with the latter having lower values of I_2.

6.04 The maximum value of I_2 for block length 3, 0.64, occurs at space 10. The minimum value, 0.49, occurring for the space range 3 - 5. At space 1 the value of I_2 is 0.59 decreasing with increase in space size to reach a minimum value and increases slightly afterwards. Between spaces 1 - 4 the values of I_2 are higher for block length 3 than for block lengths 1 and 2. Beyond space 4 this relationship is reversed. At space 4 the values of I_2 for block lengths 1, 2 and 3 coincide at 0.49.

6.05 For block length 4 the values of I_2 are slightly higher than those for block length 3 at spaces 1 - 5. At space 5 block lengths 3 and 4 have the same I_2 value, 0.50. Beyond space 5 the values of I_2 for block length 4 are lower than those for block length 3. The difference increases with increase in space size. There are two maximum values of I_2 for this block length at the extremities of the space sizes: 1 and 10. The minimum value, 0.50, occurs in the range of spaces 3 - 5.

6.06 For block length 5 the highest value for I_2 occurs at the smallest space size - 1. With increase in space size the values of I_2 decrease to reach a minimum value of about 0.52 at the space range 4 - 6. Beyond this, I_2 increases gently to reach 0.57 at space 10. At this block length the maximum value of I_2 shifts to the smallest space size, reversing the position of maximum I_2 values in the previous block lengths.

6.07 Between block lengths 5 and 10 the values of I_2 decrease with increase in space. At block length 10 the minimum value occurs at space 10 and the maximum occurs at space 1.

6.08 The values of I_2 when block lengths increase to 15 are lower than those at block length 10 for spaces 1 - 8. At about space 8 the values of I_2 for block lengths between 10 and 15 coincide, but they become higher for block length 15 with further increase in spacing. The maximum values of I_2 for block lengths 10 - 15 occur at space 1 and minimum values occur at larger spaces 5 - 8.

6.09 Block lengths greater than 15 yield lower values of I_2 than before at spaces 1 - 8. Their maximum values occur at the smallest space. With increase in space I_2 decreases to reach minimum values around space 5. A gentle increase follows as the space increases to 10. Around space 8 the values of I_2 for block lengths 10 - 20 coincide showing that increase of block length beyond 10 at this space size has no, or little, effect on the values of the exposure index.

6.10 Diagram 4.8 shows the relationship between the exposure measure I_2 and block length for a range of space sizes. The increase in block length causes an increase in I_2 for space 1 to reach a maximum value

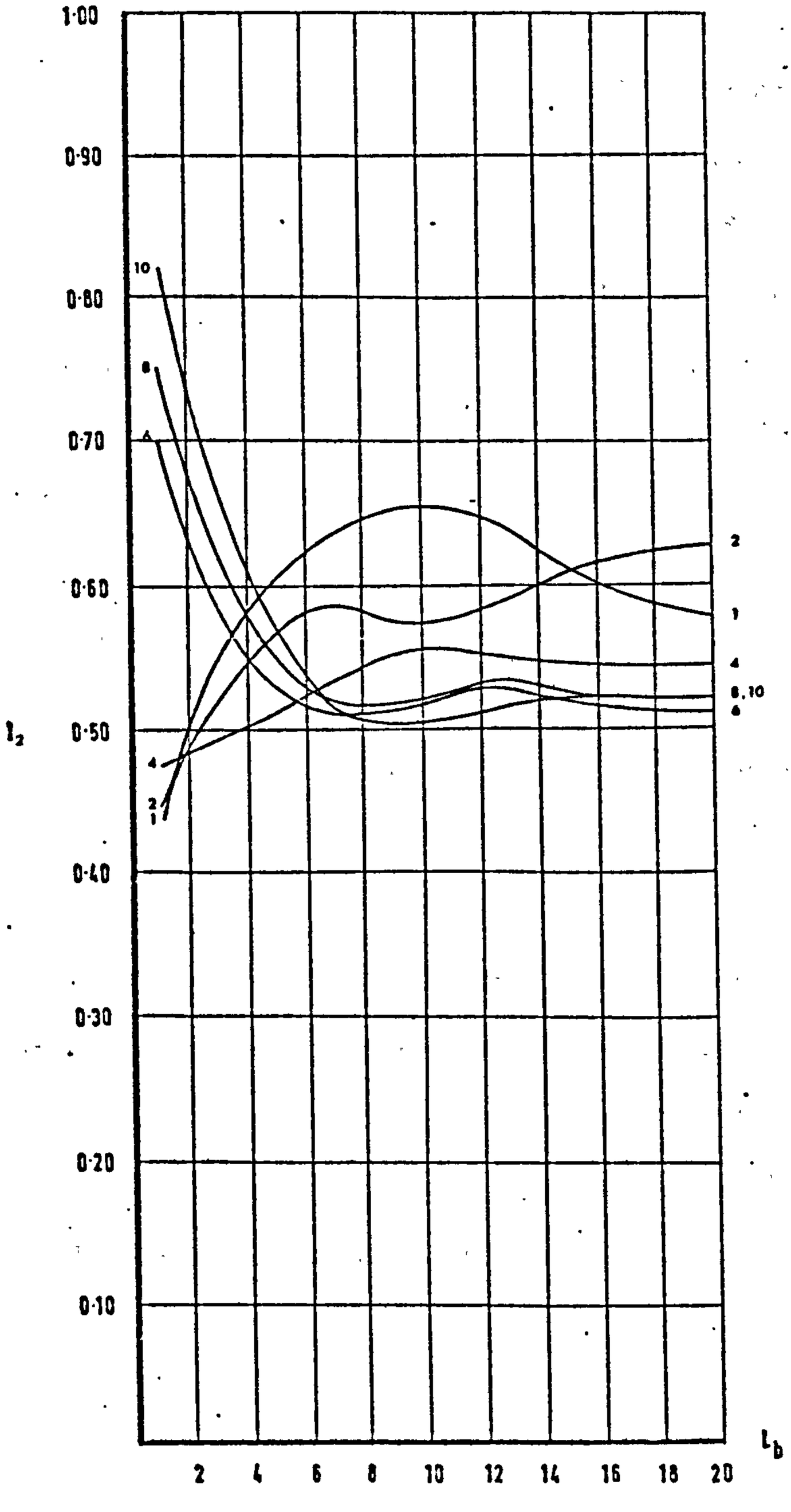


DIAGRAM 4.8 RELATION BETWEEN EXPOSURE MEASURE I_2 AND BLOCK LENGTH L_b (FOR DIFFERENT SPACE SIZES)

around block length 10. Beyond this block length I_2 decreases gradually towards block length 20.

6.11 At space size 2 the increase in block length is also accompanied by an increase in I_2. It reaches the value of 0.59 around block length 7. Towards block length 10 there is a decrease in I_2 before the values of I_2 start to increase gently towards block length 20. The value of I_2 at space 2 for block length 20 is 0.63. This is higher than the value of I_2 for the corresponding length at space 1. At block length 15 the values of I_2 for spaces 1 and 2 coincide. The difference in I_2 values for the space sizes increases with the increase in block length from 1 to 10 where the difference is largest. Further increases in block length diminish the difference between the two sets of values and they coincide at block length 15 before diverging with further increase in block length.

6.12 At space 4 the values of I_2 are slower in their increase with block length. I_2 reaches a maximum value at block length 10. The maximum value is lower than those for previous space sizes. Beyond the maximum value position I_2 shows another difference from previous behaviour at spaces 1 - 3 - it decreases in value. Its minimum value occurs at block length 1.

6.13 Increasing the space size to 6 shifts the position of maximum I_2 value to the smallest block length. Between block lengths 1 and 6 there is a relatively sharp drop in I_2 values. I_2 values remain stationary until block length 10 where it starts to increase with further increase in block length until block length 12. For the block lengths greater than 12 I_2 drops in value gently towards block length 18 where it takes

another set of stationary values until block length 20.

6.14 At space size 8 the maximum value also occurs at block length 1. I_2 drops sharply as the block length increases to 8 to take a stationary value until block length 10. Between block lengths 10 and 13 I_2 increases, but drops again towards block length 16 and remains at the same value with further increase in block length. The set of values of I_2 for space 8 is slightly higher than that for space 6.

6.15 Like spaces 6 - 8 the maximum values of I_2 for space 10 occur at block length 1. It drops sharply to take a minimum value at block length 9. From this position it increases slowly towards block length 16 where it coincides with I_2 values for space 8 and remains the same with further increase in block length. I_2 values are only higher for space 10 than those for spaces 6 - 8 at shorter block lengths.

7.00 Exposure Measure I_3:

7.01
$$I_3 = \sum_{i=1}^{10} \frac{n_i V_i}{100N}$$

7.02 Exposure indices (taking values in the range 0 - 1) were computed using I_3 for the arrangements of 20 block lengths and 10 space sizes. The results are shown in diagrams 4.9 and 4.10.

7.03 Diagram 4.9 shows plots of the values of I_3 against space size for the range of block lengths. At the smallest block length 1 the value of I_3 drops at initial increase in spacing but rises towards space 3. The increase in I_3 is rapid between spaces 3 and 6 and relatively slower beyond space 6. The maximum value of I_3 for this block length occurs at space 10 and the minimum value around space 2.

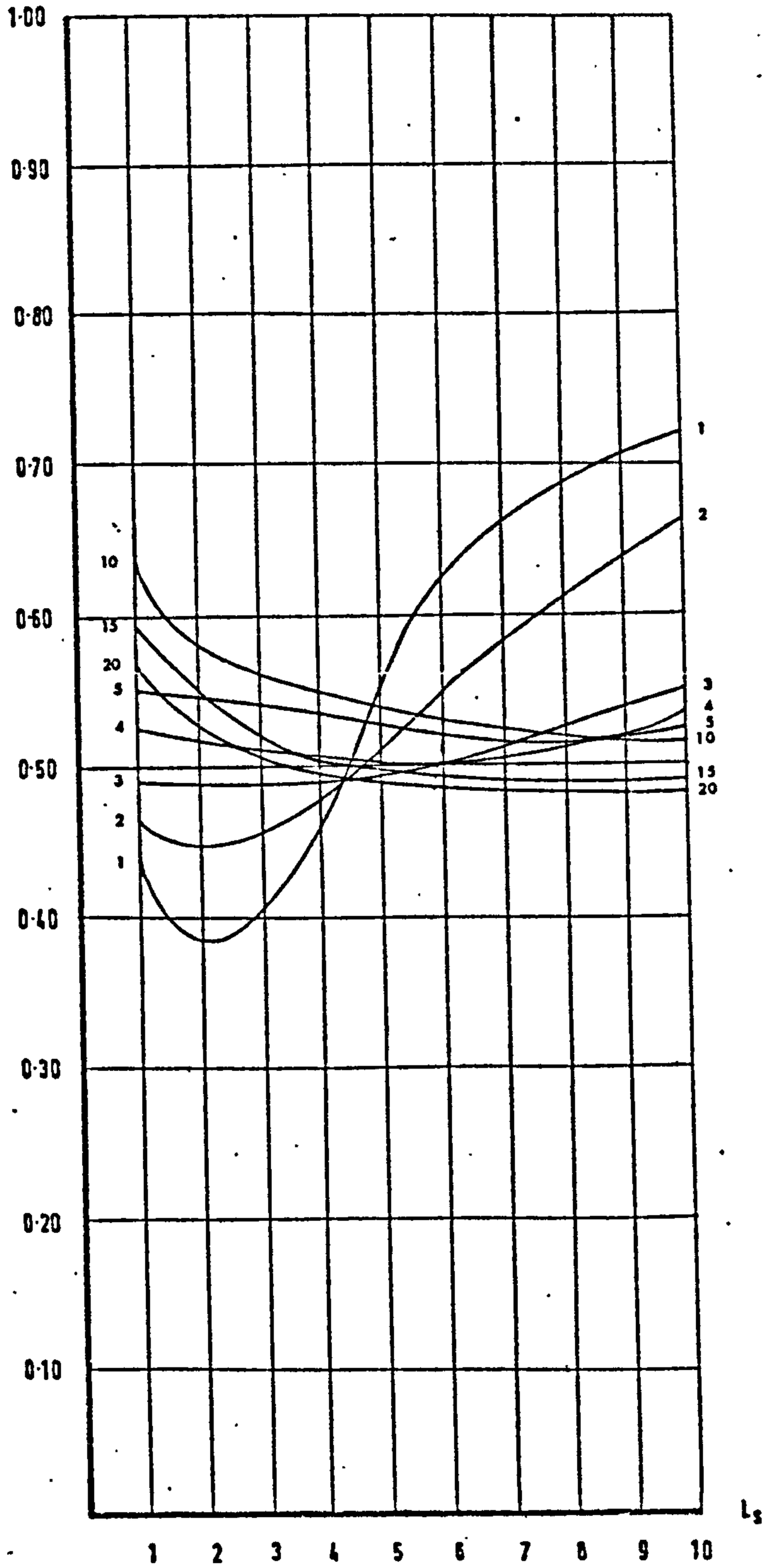


DIAGRAM 4.9 RELATION BETWEEN EXPOSURE MEASURE I_3 AND SPACE SIZE L_s (FOR DIFFERENT BLOCK LENGTHS)

7.04 For block length 2 an initial drop in the values of I_3 occurs before it rises towards space 3. The drop, however, is less pronounced than in the previous block length. Between spaces 1 and 4 the values of I_3 for this block length are higher than those for 1. I_3 takes the same value for the two block lengths around space size just after 4 and on further increase in space size block length 2 has lower values of I_3 than 1. Maximum I_3 value for this block length occurs at space 10 and the minimum value at space 2.

7.05 I_3 shows a different behaviour at block length 3 from the previous block lengths. Between spaces 1 and 4 I_3 values are stationary, but they begin to rise relatively slowly after space 4. I_3 has maximum value for this block length at space 10 and around space 4 its value coincides with those of block lengths 1 and 2. Between spaces 1 and 4 I_3 has higher values for this block length than for either 1 or 2, but this situation is reversed for spaces greater than 4.

7.06 Block length 4 shows relatively small changes in I_3 with change in space. A gentle drop in I_3 as space sizes increase leads to a stationary minimum value between spaces 5 and 7. Beyond this range I_3 rises towards a maximum value at space 10. Around spaces 4 - 5 the values of I_3 for block length 4 coincide with those of block lengths 1, 2 and 3.

7.07 The position of the maximum value of I_3 shifts to the smallest space size 1 at block length 5. I_3, however, shows little change as space size increases. It takes a minimum value around space 6 where it remains unchanged with further increase in space size.

7.08 At block length 10 the maximum value of I_3 occurs at space 1. It decreases first rapidly and then slowly as the space increases. The minimum value occurs at space 10 and I_3 values are generally higher for this block length than those for block length 5, but the difference in the two sets of values diminishes with increase in spacing. At space 9 I_3 has the same values for block lengths 5 and 10.

7.09 The increase in block length from 10 to 15 causes the sets of values for I_3 to drop but I_3 shows the same behaviour: taking a maximum value at space 1, diminishing with increase in space to take minimum values at spacing 10. At about space 4 the values of I_3 for block lengths 1, 2, 4 and 15 coincide.

7.10 Block length 20 shows the same change in I_3 as block length 15, only lower in value. Thus, its maximum value occurs at space 1, decreases gently towards a minimum value at space 6 where it remains stationary until space 10.

7.11 In diagram 4.10 the relationship between I_3 and the block length is shown for a range of spaces. The increase in block size increases I_3 at space size 1 from a minimum at block length 1 to a maximum around block length 10. For block lengths greater than 10 the value of I_3 decreases gradually to attain a stationary value between block lengths 18 - 20.

7.12 The values for I_3 for space 2 are lower than those for space 1, but the pattern of change with increase in block length is the same.

7.13 Between block length 1 and 3 space size 4 has higher values of I_3

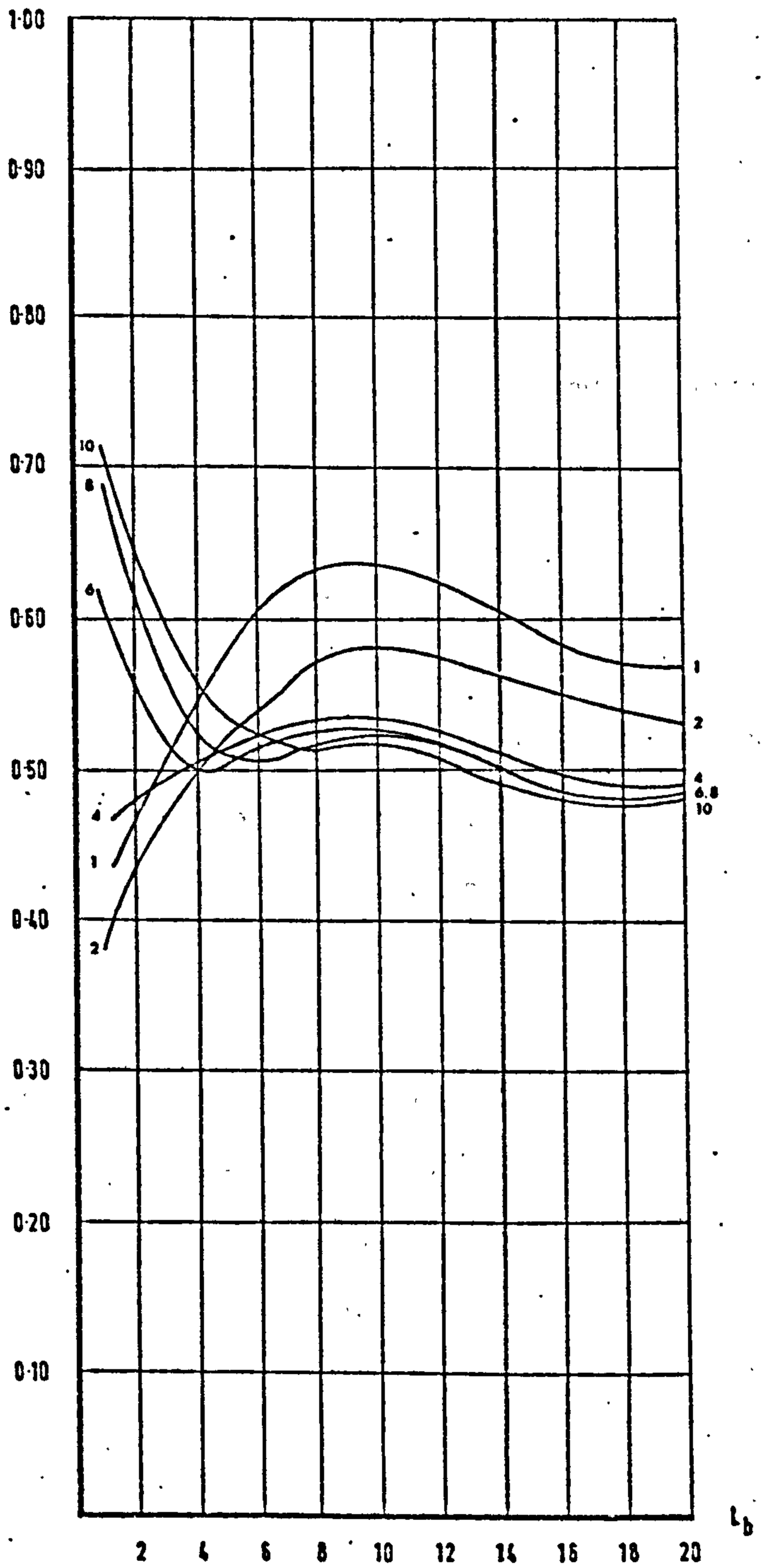


DIAGRAM 4.10 RELATION BETWEEN EXPOSURE MEASURE I_3 AND BLOCK LENGTH L_b
(FOR DIFFERENT SPACE SIZES)

than previous spaces. Increasing block length increases the value of I_3 slowly to reach a maximum at block length 10 and then it decreases with further increase in block length.

7.14 At space 6 the position of the maximum value of I_3 shifts to block length 1, dropping sharply towards block length 4. Between block lengths 4 and 10 the value of I_3 increases before it continues to drop again, reaching a minimum value at block length 16. It remains at this minimum value until block length 20.

7.15 The same pattern of change in the values for I_3 for space 6 with change in block length is shown by spaces 8 and 10. The maximum values occur at block length 1, dropping sharply towards block length 6 and a slow increase follows towards block length 10. From block length 10, I_3 values for spaces 8 and 6 are very close until block length 14, where they coincide.

7.16 Between block length 1 and 8 the values of I_3 for spacing 10 is higher than those for spaces 6 and 8 but they become slightly less after that. As before, the maximum value of I_3 occurs at block length 1 but the minimum value is reached at block length 16.

8.00 Exposure Measure I_4:

8.01
$$I_4 = \sum_{i=0}^{100} \frac{V_i \, a_i}{100A}$$

8.02 The intervals in the values of the equal velocity lines used here are 10%. In computing an exposure index by this formulation, the quantitative visual representation developed in chapter 3 was particularly useful. However, the diagrams from which areas were calculated were twice

as big in scale and drawn on graph paper for convenience of calculating the areas.

8.03 Diagram 4.11 shows the relationship between I_4 and block length for a set of space sizes and diagram 4.12 shows the relationship between I_4 and space size for a set of block lengths.

8.04 At block length 1, diagram 4.11, the value of I_4 falls as the space increases from 1 to 2 and then rises sharply towards space 7. Between space 7 and 10 the values of I_4 continue to increase, but relatively slowly, and the maximum I_4 value is reached at space 10. The minimum value for this block length occurs at space 2.

8.05 When the block length is increased to 2, the values of I_4 between spaces 1 and 4.5 become higher than those for block length 1, but lower after that. Therefore, the values of I_4 for the two block sizes coincide around space 5. As the space size increases from 1, the values of I_4 fall until space 3, beyond which they begin to rise steadily, reaching a maximum value at space 10. The minimum value of I_4 for this block length occurs around spaces 2 - 3. The minimum value of I_4 for block length 2 is higher than that for block length 1, while the maximum values show the opposite.

8.06 I_4 takes higher values for block length 3 than for block lengths 1 and 2 between space sizes 1 - 4.5, but lower values than either beyond this range. Between space 1 and 3 there is a relatively sharper drop in the values of I_4 for block length 3. The main change in the behaviour of I_4 in this case is the shift of the maximum value from the largest space to the smallest - space 1. The minimum value occurs at space 3.

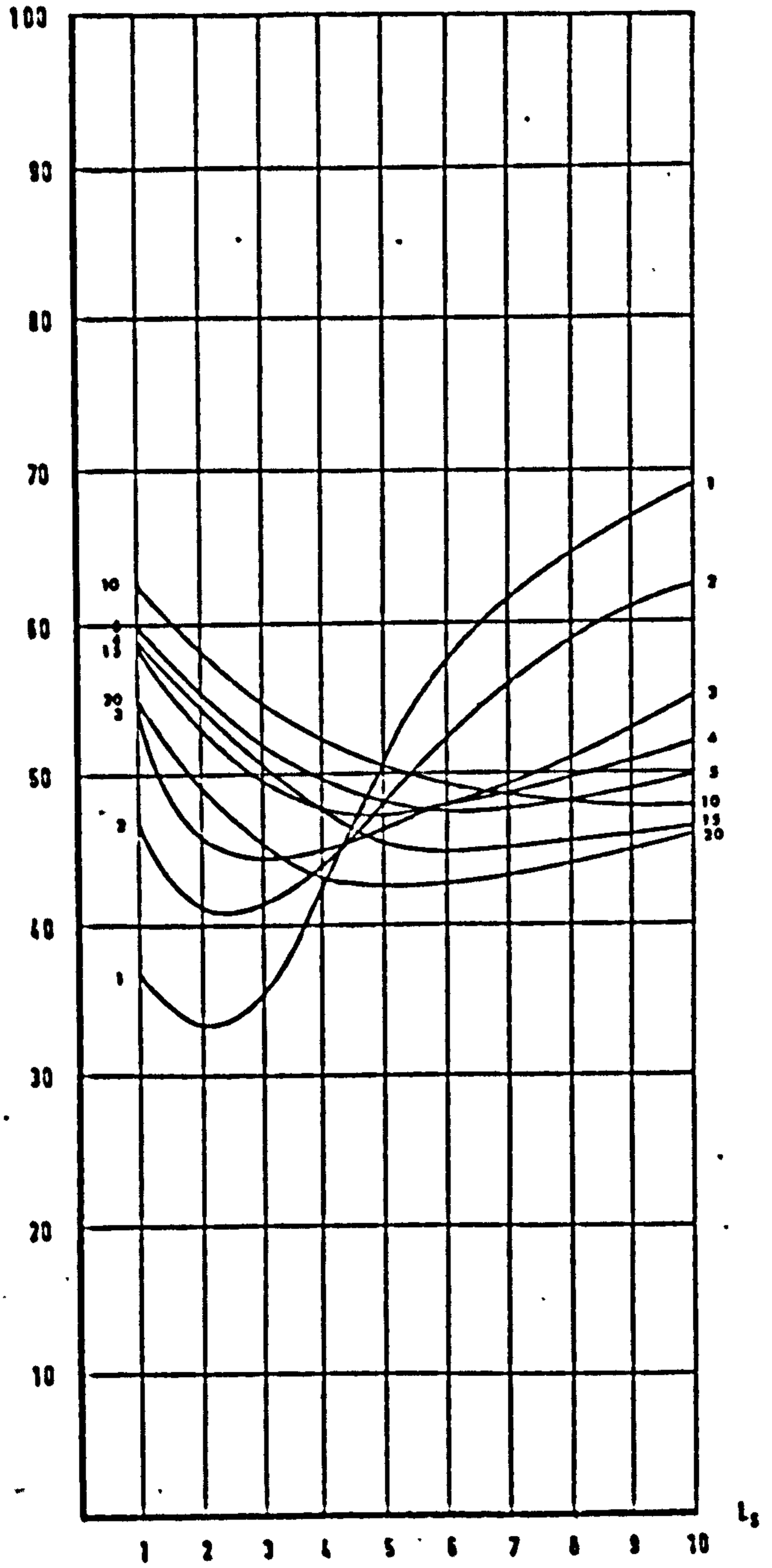


DIAGRAM 4.11 RELATION BETWEEN EXPOSURE MEASURE I_4 AND SPACE SIZE L_s (FOR DIFFERENT BLOCK LENGTHS).

Beyond this value I_4 continues with an increase until it takes a second maximum value at space 10. At about space 4.5 the value of I_4 for space 3 coincides with those of spaces 1 and 2.

8.07 At block length 4, the maximum value of I_4 occurs at space 1. I_4 decreases with increase in space to reach a minimum at space 5. Further increase in space size increases the value of I_4 towards space 10. At around space 5 the values of I_4 for this block length and for block lengths 1 and 2 coincide. At space 6 block lengths 4 and 3 have the same value of I_4.

8.09 Between spaces 1 and 6 the values of I_4 are higher for block length 5 than for block length 4, but they become lower after that. As in the case of block length 4, the position of maximum I_4 is at the smallest space size - space 1. It drops as space increases to reach its minimum at space 6. This minimum value of I_4 persists until space 8, but I_4 increases slightly with further increase in space towards space 10. For block lengths 3, 4 and 5 the values of I_4 coincide at space 6.

8.10 At block length 10 the position of maximum I_4 is at space 1 and the minimum occurs first at space 8 and I_4 remains stationary until space 10. The decrease in the values of I_4 as the space increases to 8 is relatively gentle.

8.11 The increase of the block length to 15 shows a slight change in the behaviour of I_4 from block length 10. The maximum I_4 occurs at space 1 and I_4 drops in value to reach the minimum at space 6, beyond which it rises slowly towards space 10. The values of I_4 for this block length are generally lower than for block length 10. The difference between the

two sets of values is largest between spaces 4 - 6, but it diminishes with further increase in space.

8.12 At block length 20, the position of maximum I_4 is the same as in the previous two cases - at the small space size, but minimum I_4 occurs between spaces 4 - 6. On further increase of space beyond 6, the values of I_4 increase towards space 10. The set of values for I_4 for this block length is lower than that at block length 15 with largest differences occurring at smaller space sizes, but decreasing with increase in spacing.

8.13 Diagram 4.12 shows the relationship between I_4 and block length for different space sizes. For space 1 the lowest value of I_4 occurs at block length 1 and it increases with increase in block length to reach a maximum value at block length range 8 - 10. On further increase of block length the value of I_4 falls steadily towards block length 20.

8.14 At spacing 2 the values of I_4 are lower than those for spacing 1. The behaviour of I_4 with change in block length is the same as in the previous case - minimum value at block length 1 increasing to a maximum between 8 - 10, but decreases with further increase in block length.

8.15 Spacing 4 shows higher values of I_4 than the previous space size between block length 1 - 3. At block length 3 the values of I_4 for spaces 2 and 4 coincide. Beyond this block length space 4 has lower I_4 values than space 2. The minimum value of I_4 for this spacing occurs at block length 1 and I_4 increases with increase in block length until it reaches maximum value at block length 10. Beyond this block length I_4 falls in value steadily until block length 18 where it attains a

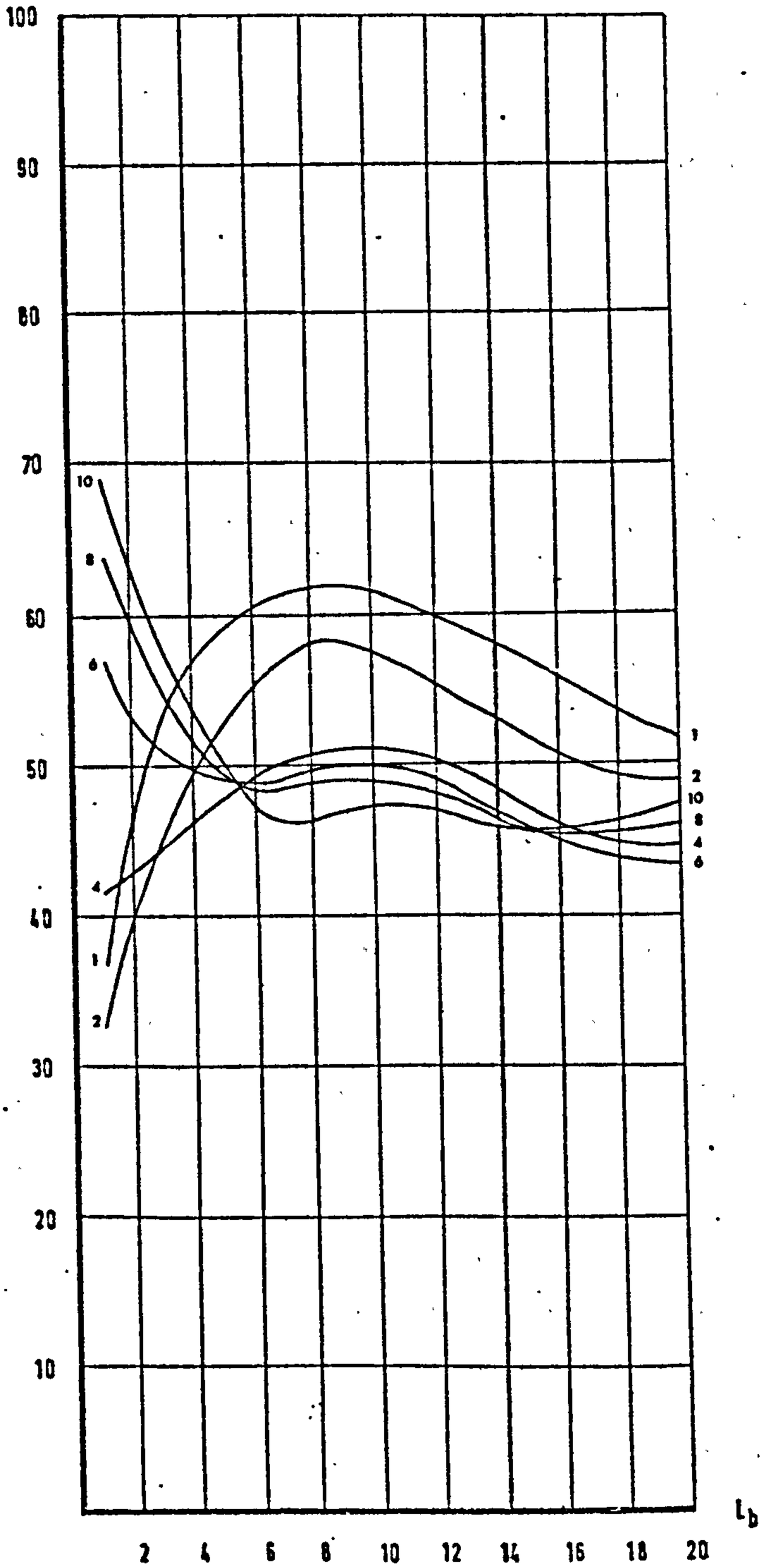


DIAGRAM 4.12 RELATION BETWEEN EXPOSURE MEASURE I_4 AND BLOCK LENGTH L_b (FOR DIFFERENT SPACE SIZES)

stationary value unaffected by further increases in block length.

8.16 The position of the maximum value of I_4 shifts to the smallest block length when the space size is 6. With increase in block length I_4 falls gradually to reach an almost stationary value between block lengths 6 - 11. Beyond this range, I_4 values continue to fall to reach a minimum at block length 17 and remains unchanged with further increase in block length.

8.17 For space size 8, the values of I_4 are higher than those for spacing 6 at block length range 1 - 6. The I_4 values for the two space sets coincide around space 6 beyond which I_4 has lower values for space 8 than for space 6. This relationship continues until block length 15, beyond which the initial relationship between the I_4 values of the two space sets is re-established. Maximum I_4 for space 8 occurs at block length 15 with values of I_4 falling relatively rapidly towards block length 6. Towards block length 10 there is a slight increase in the values of I_4 but beyond this block length I_4 continues to fall until block length 15 with no further changes with increase in block length.

8.18 The highest value of I_4 for the whole set of arrangements is achieved at block length 1 for space 10. With increase in block length I_4 falls to a first minimum value at block length 7. Between this block length and block length 10 there is a slight increase in I_4 values and I_4 continues to fall beyond this block length range, reaching a second minimum at block length 15 and remains almost stationary at its value at this block length. Between block lengths 1 - 6 the values of I_4 for space 10 are higher than those for space 8. Around block length 6 this relationship is reversed so that I_4 has lower values for

space 10 than for space 8. This situation continues until block length 15, beyond which the previous relationship emerges again.

9.00 Exposure Measure I_5:

9.01
$$I_5 = \sum_{i=0}^{100} \left[a_i \ \frac{(V_i + V_{i+10})}{2} \right] \Big/ 100A$$

9.02 The 10% interval is an optimal interval between larger intervals which give lower values for I_5 and smaller intervals which makes calculation of areas more difficult.
The results of the computations of I_5 for the range of block lengths and space sizes is given in diagrams 4.13 and 4.14.

9.03 Diagram 4.13 shows the relationship between I_5 and the size of the space between the blocks for a range of block lengths. Block length 1 shows a value of 0.42 for I_5 at space 1. This falls to 0.38 on increasing the space to 2, but I_5 increases rapidly with further increase in space size to reach a maximum value of 0.74 at space 10.

9.04 Block length 2 has higher values of I_5 than block length 1 in the space range 1 - 4.5, but lower values beyond that, thus the I_5 values for the two space sizes coincide at about space 4.5. At space 1, the value of I_5 is 0.52 but it falls to a minimum value of 0.46 at the space range 2 - 3. With further increase in space size I_5 values increase relatively rapidly until space 8, but slower after that to reach a maximum value of 0.68 at space 10.

9.05 Increasing block length to 3 causes I_5 to take higher values than those for previous block lengths in the space size range 1 - 4.5.
At around space 4.5 I_5 values for block lengths 1, 2 and 3 coincide, but

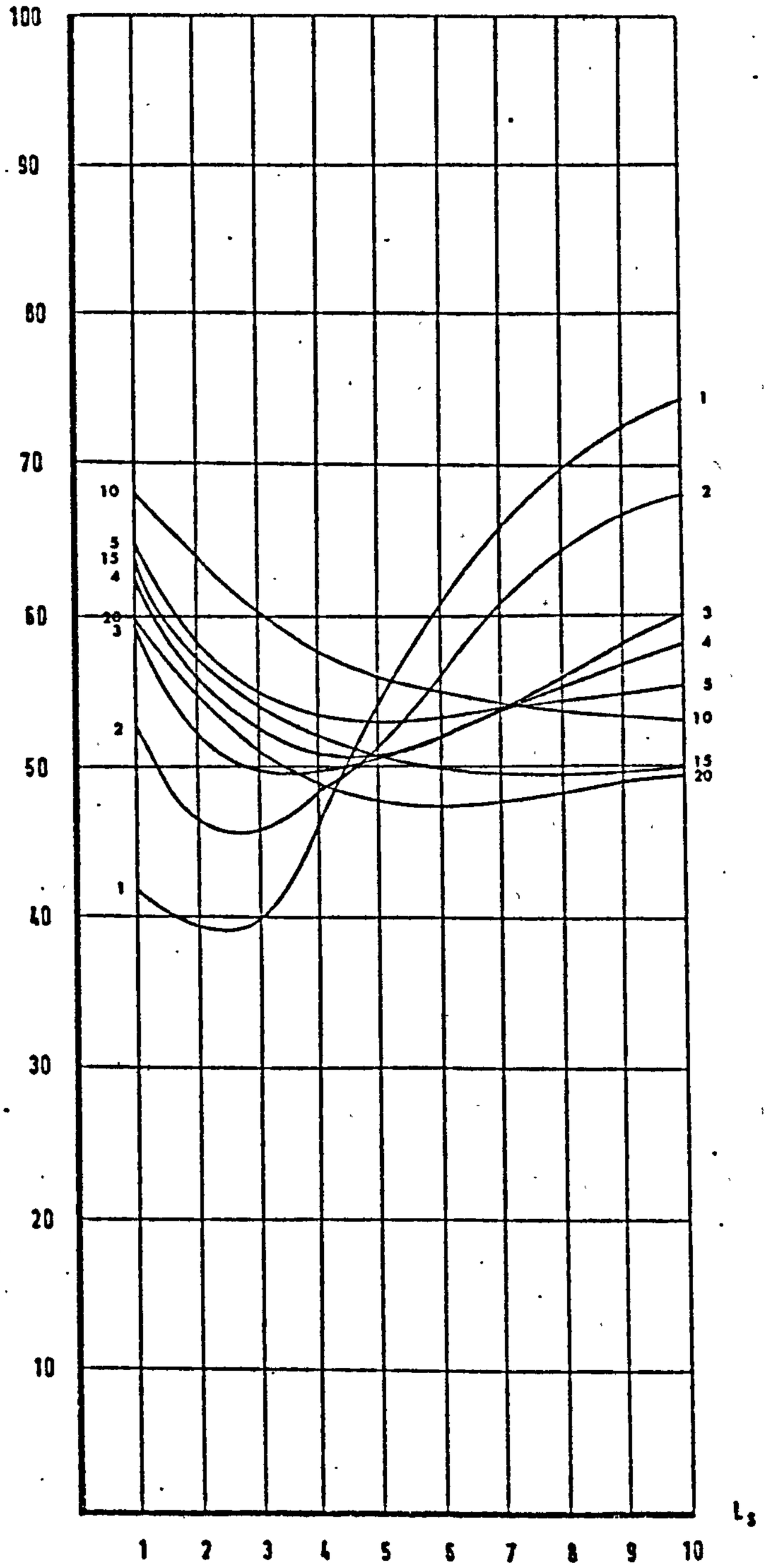


DIAGRAM 4.13 RELATION BETWEEN EXPOSURE INDEX I_5 AND SPACE SIZE L_5 (FOR DIFFERENT BLOCK LENGTHS)

they become lower for block length 3 beyond that. The maximum value of I_5 for this block length occurs at space 10. This value, 0.60, is slightly higher than that for space 1. The minimum value of I_5 is 0.79, occurring at about space 3. The increase in I_5 values beyond the minimum is slower than that for block length 1 and 2.

9.06 At block length 4, the position of the maximum value of I_5 shifts from space 10, in the previous block lengths, to space 1. Its value is 0.62. I_5 decreases with increase in space to a minimum value of 0.51 at space 4. Further increase in space size causes I_5 to increase gradually reaching a value of 0.58 at space 10. Between spaces 1 - 6, the values of I_5 for this block length are higher than those for block length 3. At about space 6, the two values coincide at 0.52. For spaces greater than 6 the values of I_5 are lower for block length 4 than those for block length 3 - the difference in values being much lower than that between block lengths 1 and 2 or 2 and 3.

9.07 The maximum value of I_5 for block length 5 is 0.64 occurring at space 1. It decreases with increase in space to reach a minimum value of 0.53 at the space range 4 - 5. On further increase in space the value of I_5 increases very slowly to reach 0.55 at space 10. Between spaces 1 - 7 the values of I_5 for this block length are higher than for block length 4 but for space sizes larger than 7 this situation is reversed and thus the two block sizes have the same value of I_5 around space 7.

9.08 For block length 10 the maximum and minimum values of I_5 are respectively at the smallest and largest space sizes. At this block length the value of I_5 decreases steadily with increase in space. The maximum

I_5 value is 0.67 and the minimum of 0.53. Between spaces 1 - 7.5 this block length shows higher values of I_5 than block length 5, but lower values after that. At about space 7.5 the value of I_5 for this block length and block length 5 coincide.

9.09 Increasing the block length to 15 causes the set of I_5 values for different spacing to drop in relation to the previous block length. It is similar, however, in that the maximum value of I_5 occurs at space 1 and is 0.63. The position of the minimum I_5 is different from block length 10 and it occurs around space 5.5 with a value of 0.50. I_5 remains unchanged with further increase in space size.

9.10 At block length 20 the values of I_5 for different spaces are lower than those for the previous block length. Initially, the difference is relatively large, but it decreases with increase in space size. The maximum value of I_5, occurring at space 1, is 0.59. I_5 falls with increase in space to reach a minimum value of 0.47 at space 6. With further increase in space the value of I_5 increases slightly to reach 0.49 at space 10.

9.11 In diagram 4.14 the relationship between I_5 and block length is shown for a set of space sizes.

At block length 1, the value of I_5 is 0.42 for spacing 1. This increases with increase in block length to a maximum of 0.67 in the block length range 8 - 10. Further increases in block length decrease the value of I_5 until it reaches 0.58 at block lengths 19 and 20.

9.12 Space size 2 has lower values of I_5 but their pattern of change with increase in block length is the same as for space 1. The minimum

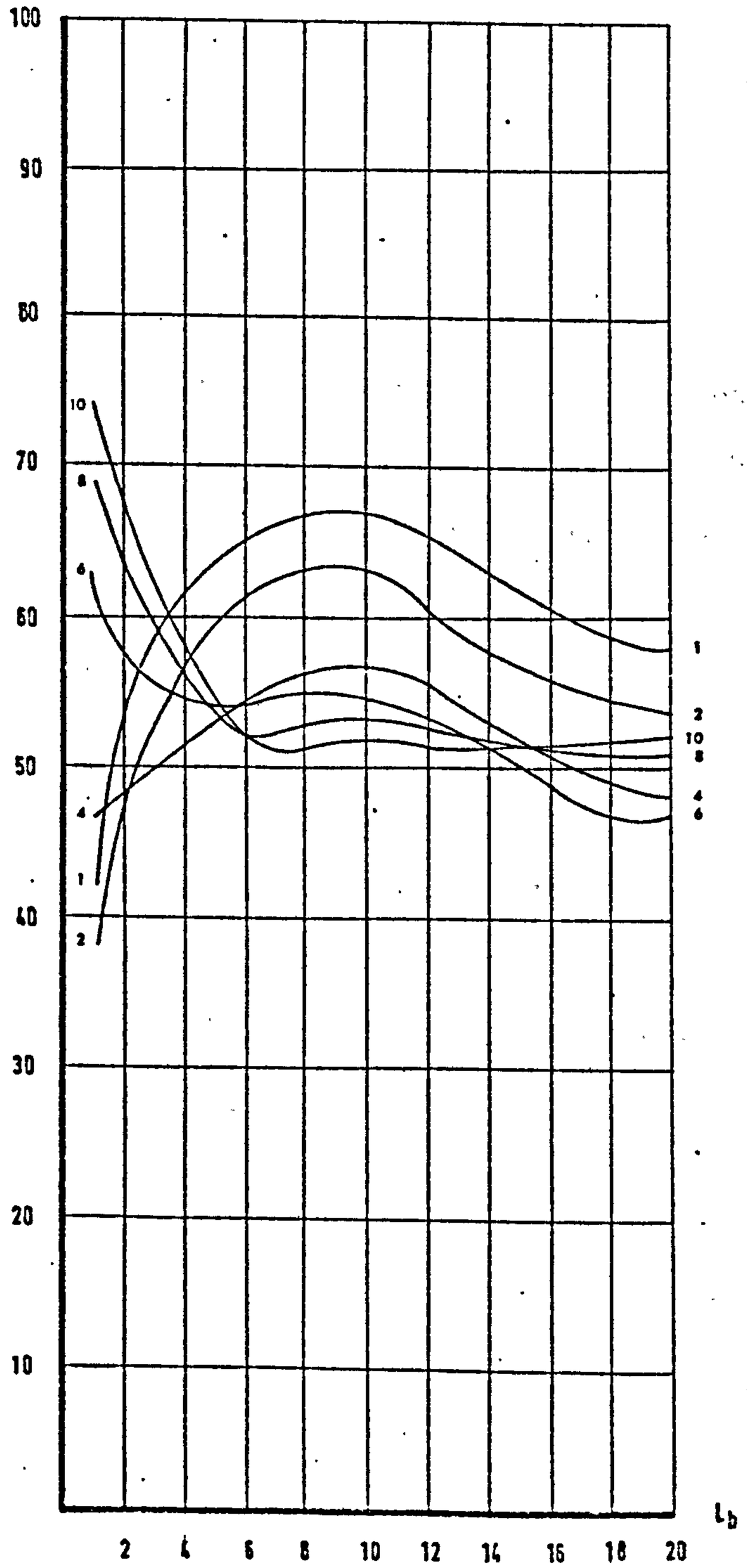


DIAGRAM 4.14 RELATION BETWEEN EXPOSURE INDEX I_5 AND BLOCK LENGTH L_b
(FOR DIFFERENT SPACE SIZES)

value of I_5 is 0.38, occurring at block length 1. I_5 increases with increase of block length to reach a maximum value of 0.63 at the block length range 8 - 10. With further increase in block length beyond 10 the value of I_5 decreases to a value of 0.54 at block length 18 and remains stationary at that until block length 20.

9.13 For space size 4, the value of I_5 at block length 1, 0.47, is greater than in the previous two space sizes. At block length 2 it coincides with that of space 2 at 0.48. With increase in block length I_5 increases less sharply than in spaces 1 and 2 and it reaches a maximum of 0.57 at block length 10. Further increase in block length decreases I_5 until it takes a value of 0.48 at block lengths 19 and 20.

9.14 The increase in space size to 6 shifts the position of maximum I_5 to the shortest block length and the minimum to the larger block lengths 18, 19 and 20. The maximum value of I_5 is 0.62 which decreases with increase in block length to reach 0.54 at block length 6. It remains almost stationary at this value until block length 10 and then continues to fall to the minimum value of 0.47 at spaces 18, 19 and 20. Between block lengths 1 - 6 the values of I_5 for this space are higher than at space 4. Around block length 6 the two space sizes have the same value, 0.54, of I_5. For block lengths greater than 6 space 6 shows lower values of I_5 than space 4.

9.15 At space size 8 the maximum value of I_5 is 0.69 occurring at block length 1. It drops sharply to 0.52 at block length 6, staying almost stationary at this value until block length 15. Beyond this it drops to 0.51 at block length 16 and it remains stationary at this value with further increase in block length.

9.16 The maximum value of I_5 at space size 10 is 0.74 occurring at block length 1. At block length 6 it has a large drop in value to 0.52. It coincides with that of space 8 at block length 7, where its minimum value of 0.51 occurs. Between block lengths 8 - 20 the values of I_5 fluctuate between 0.51 and 0.52. They can be regarded as almost stationary for this range of block lengths.

10.00 Exposure Measure I_6:

10.01
$$I_6 = \sum_{i=1}^{i=N} \left[\frac{a_i (V_{i_1} + V_{i_2} + V_{i_3})}{3} \right] \Big/ 100A$$

10.02 The values and the behaviour of this exposure measure are very close to the previous one - I_5. It is stated here only for completion.

10.03 This measure, however, is more flexible than I_5. I_5 requires speed contours to be constructed. In some cases, the flow may be of such complexity that this is not always possible. In such cases, I_6 can be conveniently used.

11.00 COMPARISON BETWEEN THE DIFFERENT MEASURES OF EXPOSURE

11.01 The measures of exposure have different formulations but they are all similar in that they describe an average property of a form-flow relationship. In the preceding computations, the same basic data was used. In the case of measures I_0, I_1, I_2 and I_3 the speed measurements in the relevant plane have been used directly to compute the exposure index. In measures I_4 and I_5 these measurements were used to interpolate speed contours. (For I_6 they were used to construct triangular exposure areas.) A set of such lines at appropriate intervals defines the spatial distribution of the speeds throughout the plane in a manner

that point measurements fail to do. This aspect, reflected in the exposure index values, constitutes the main difference between the first set of measures I_0, I_1, I_2, I_3 and the second set I_4, I_5 and I_6.

11.02 This section will discuss the differences in estimation of exposure indices by different exposure measures and the differences in the behaviour of these measures in relation to change in form. These differences are mainly due to the way in which the measures are formulated. In the next section, the sample size as another source of differences will be investigated. By studying the sensitivity of each of the measures to sample size and its effect, the appropriate measure which is least sensitive to sample size, will be selected as a reliable measure of exposure with least data requirements.

11.03 In diagrams 4.16 - 4.23 the exposure measures are plotted for different space sizes and block lengths. Diagrams 4.16 - 4.20 show the estimations of exposure against space size for a set of block lengths. Diagrams 4.21 -.23 show the estimations of exposure against block length for a range of space sizes.

11.04 In diagram 4.16 the different measures of exposure are compared at block size 1 at different space sizes. I_6 shows the highest values of exposure whereas I_4 shows the lowest values. I_3 and I_5 show fairly close values which diverge widely at space size 10. The difference between I_0 and I_2 is large at the smaller space sizes but decreases as the space increases. I_1 and I_2 show the same value of exposure index at space 5. Before this space I_2 has lower values than I_1 but higher values for spaces greater than 5. I_3, I_4 and I_5 show a drop in values when the spacing increases from 1 to 2 and an increase in values after that.

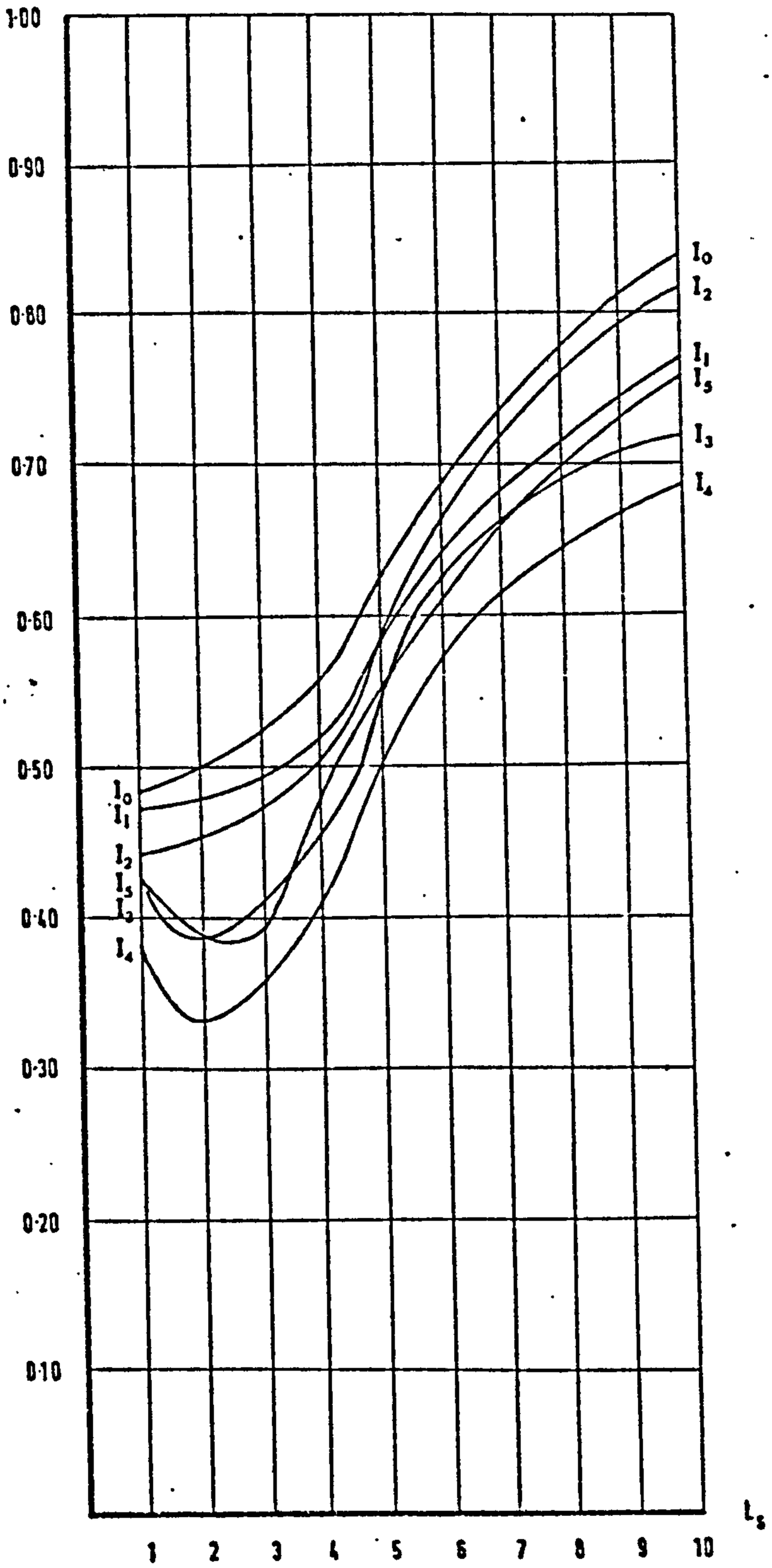


DIAGRAM 4.16 COMPARISON BETWEEN THE DIFFERENT MEASURES OF EXPOSURE AT BLOCK LENGTH 1 FOR DIFFERENT SPACE SIZES

This behaviour is not shown by any of I_0, I_1 or I_2 which increase first slowly and then rapidly with increase in spacing. Although I_3 and I_5 show the closest index values in this arrangement, they have alternatively higher and lower values relative to each other as the space increases. The range in differences in estimations of the exposure index is largest at small space sizes where it reaches 17% at space 2, and at larger space sizes where it reaches 16% at space 10. In the intermediate spaces the discrepancy is relatively smaller, e.g., at space 5 it is 12%.

11.05 A comparison between the different measures of exposure at block length 3 is shown in diagram 4.17 for different space sizes. It shows that the highest values of exposure are given by I_0. I_3 shows the lowest values in spaces 1 and 2. For spaces greater than 2 the lowest values are given by I_4. I_5 and I_2 show coinciding values at the space range 1 - 5. Beyond space 5 I_2 and I_5 diverge in values, with I_2 showing higher values of exposure than I_5. For spaces greater than 6, I_1, I_2 and I_3 are relatively close in values. At space 1 I_1 is slightly lower than I_2 but it takes higher values as the space increases until space 6.5 where its values become smaller than those of I_2. The six measures show maximum values of exposure at the largest space sizes, but minimum exposure values occur over the range 3 - 5 of space sizes. I_3 maintains a stationary minimum value between spaces 1 - 4. The measures differ in their sensitivity to change in form showing different ranges between their respective minimum and maximum values of exposure. I_0, I_1 and I_3 have relatively smaller ranges, whereas I_2, I_4 and I_5 show larger differences between minimum and maximum values. In general, the differences between the highest and the lowest estimations are relatively smaller than in the case of block length 1 and have values of

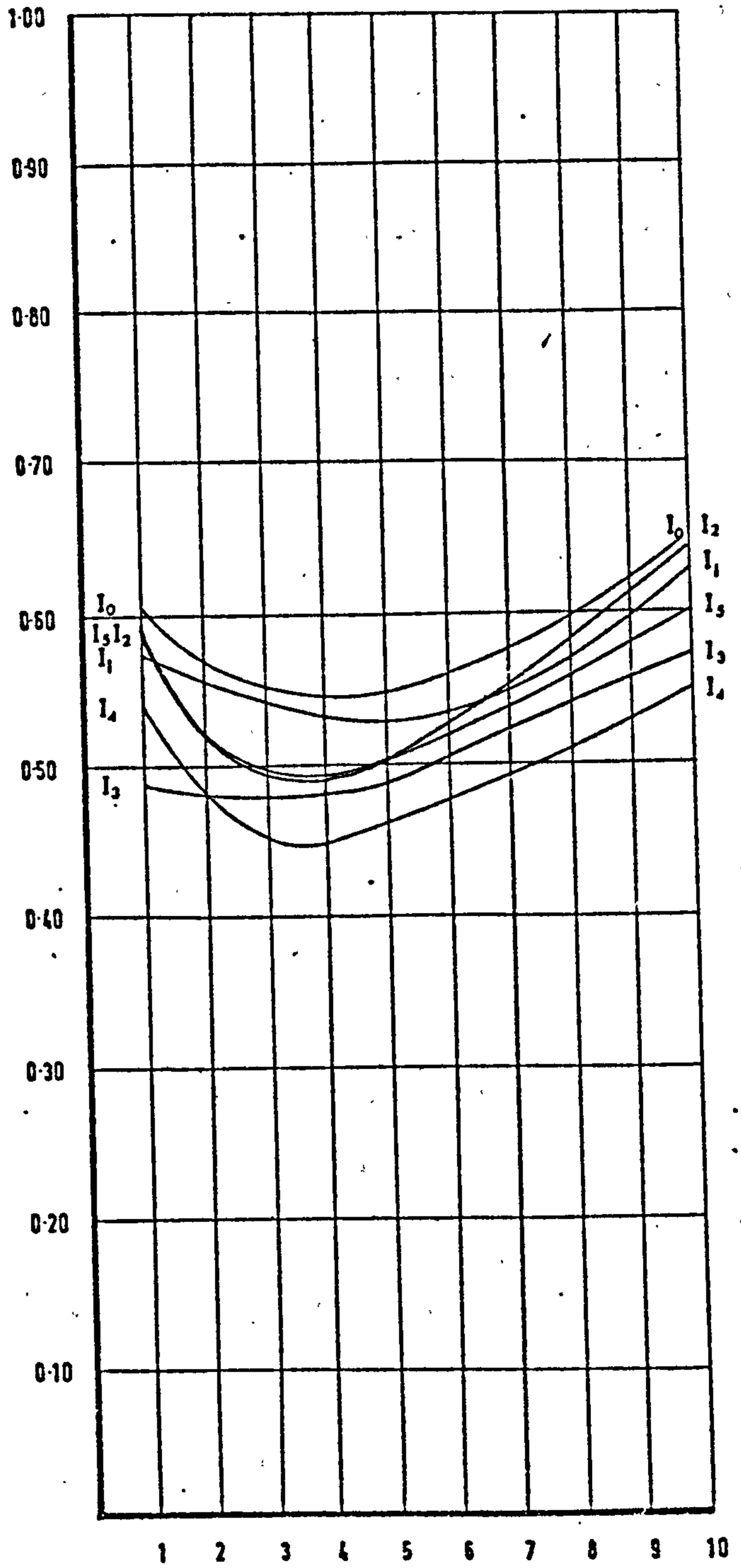


DIAGRAM 4.17 COMPARISON BETWEEN THE DIFFERENT MEASURES OF EXPOSURE AT BLOCK LENGTH 3 FOR DIFFERENT SPACE SIZES

about 9 - 10%.

11.06 Comparing the different measures of exposure at block size 5, diagram 4.18, shows that the difference between the highest and lowest estimations is less than in the previous arrangements, and it takes values of about 8 - 9%. The highest exposure values are given by I_0. In the space size range 1 - 2.5 the lowest estimations are given by I_3. For spaces greater than 2.5 the lowest values of exposure are given by I_4. All measures agree on the position of the maximum exposure values, but they differ as to the position of the minimum. The maximum exposure values occur at space size 1. For measures I_1, I_2 and I_5 the minimum occurs in the space range 4 - 6 whereas for measures I_0, I_3 and I_4 the minimum occurs around space size 7. I_2 and I_5 show closest values with I_5 slightly higher at the space range 1 - 8.5 but lower for spaces larger than 8.5. This is different from the previous arrangement where I_2 and I_5 were either coinciding or I_2 had higher values than I_5. At the smallest space sizes I_1 and I_5 also show little difference and at about space 2 they coincide. As the space increases, the difference between I_1 and I_5 increases with I_1 having higher values. The largest difference between the values of the two measures occurs around space 5, but diminishes with further increase in space size. The range in the maximum and minimum values varies with the measures. The lowest range is shown by I_3 (about 3%) while I_5 shows a range four times as much - 12%. Further, I_3 shows an almost linear relationship between exposure and space size for this block length, whereas the other measures show non-linear relationships.

11.07 Diagram 4.19 shows a comparison between the different measures of exposure at block length 10 for different space sizes. The difference

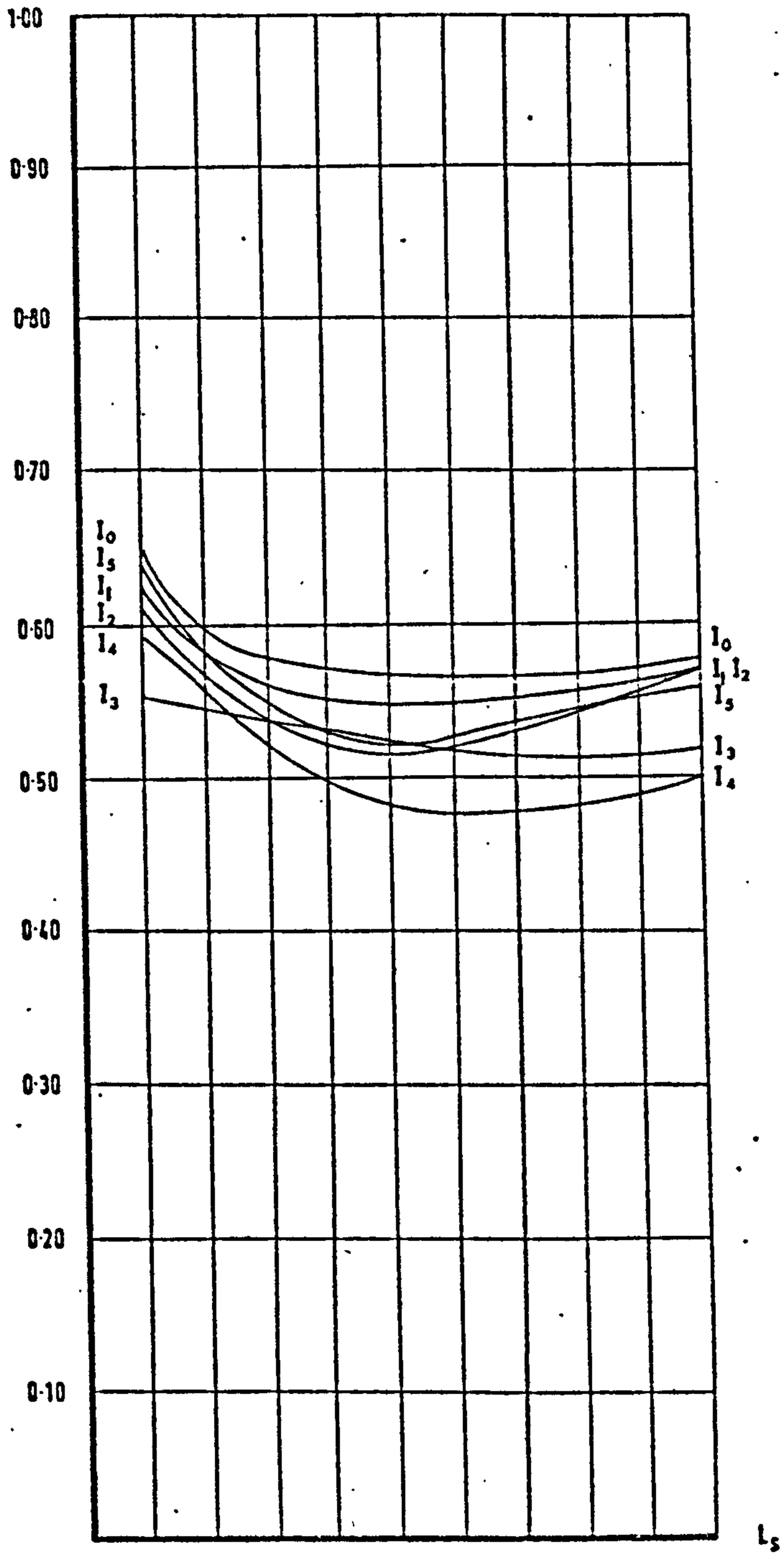


DIAGRAM 4.18 COMPARISON BETWEEN THE DIFFERENT MEASURES OF EXPOSURE AT BLOCK LENGTH 5 FOR DIFFERENT SPACE SIZES

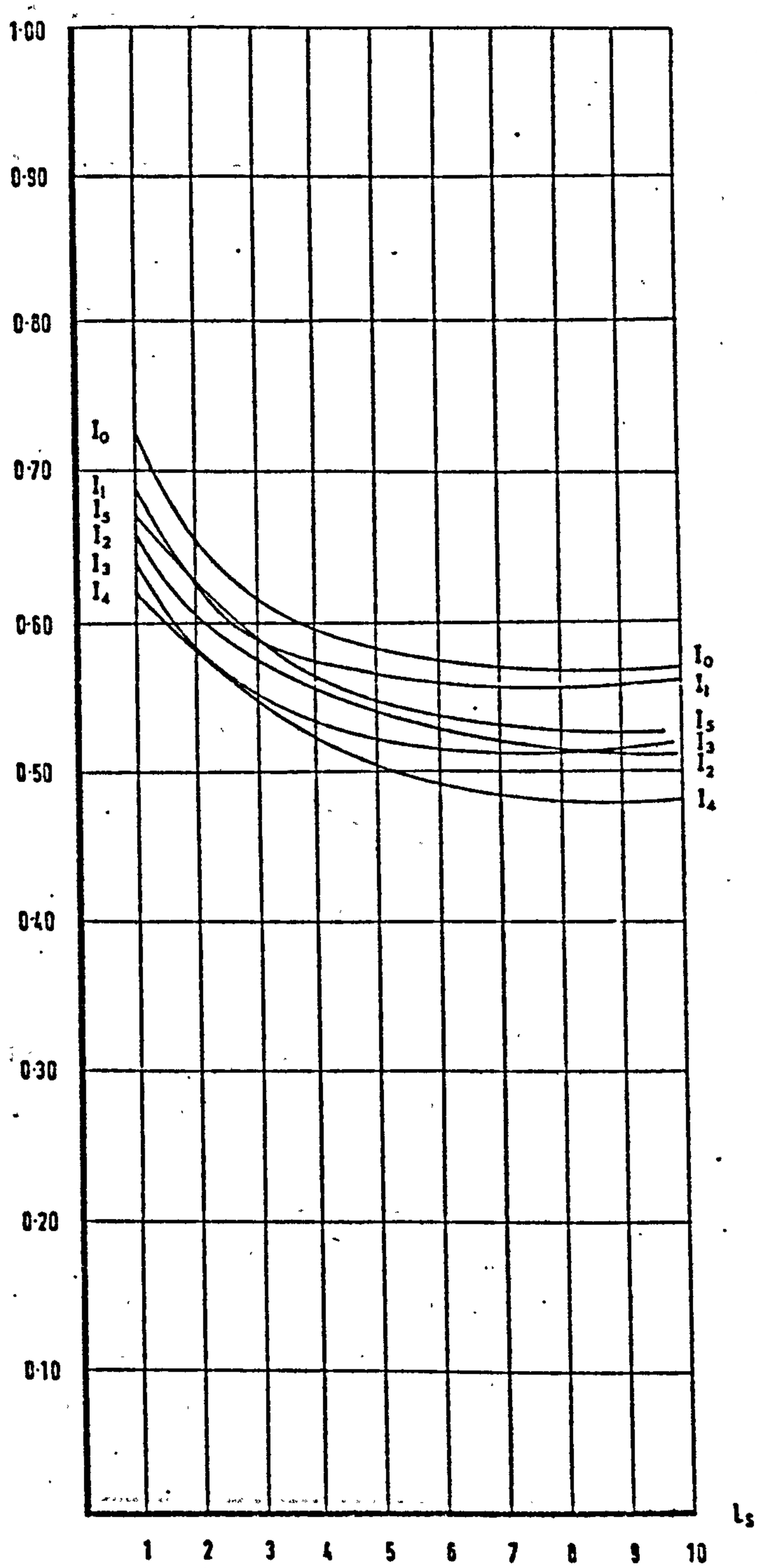


DIAGRAM 4.19 COMPARISON BETWEEN THE DIFFERENT MEASURES OF EXPOSURE AT BLOCK LENGTH 10 FOR DIFFERENT SPACE SIZES

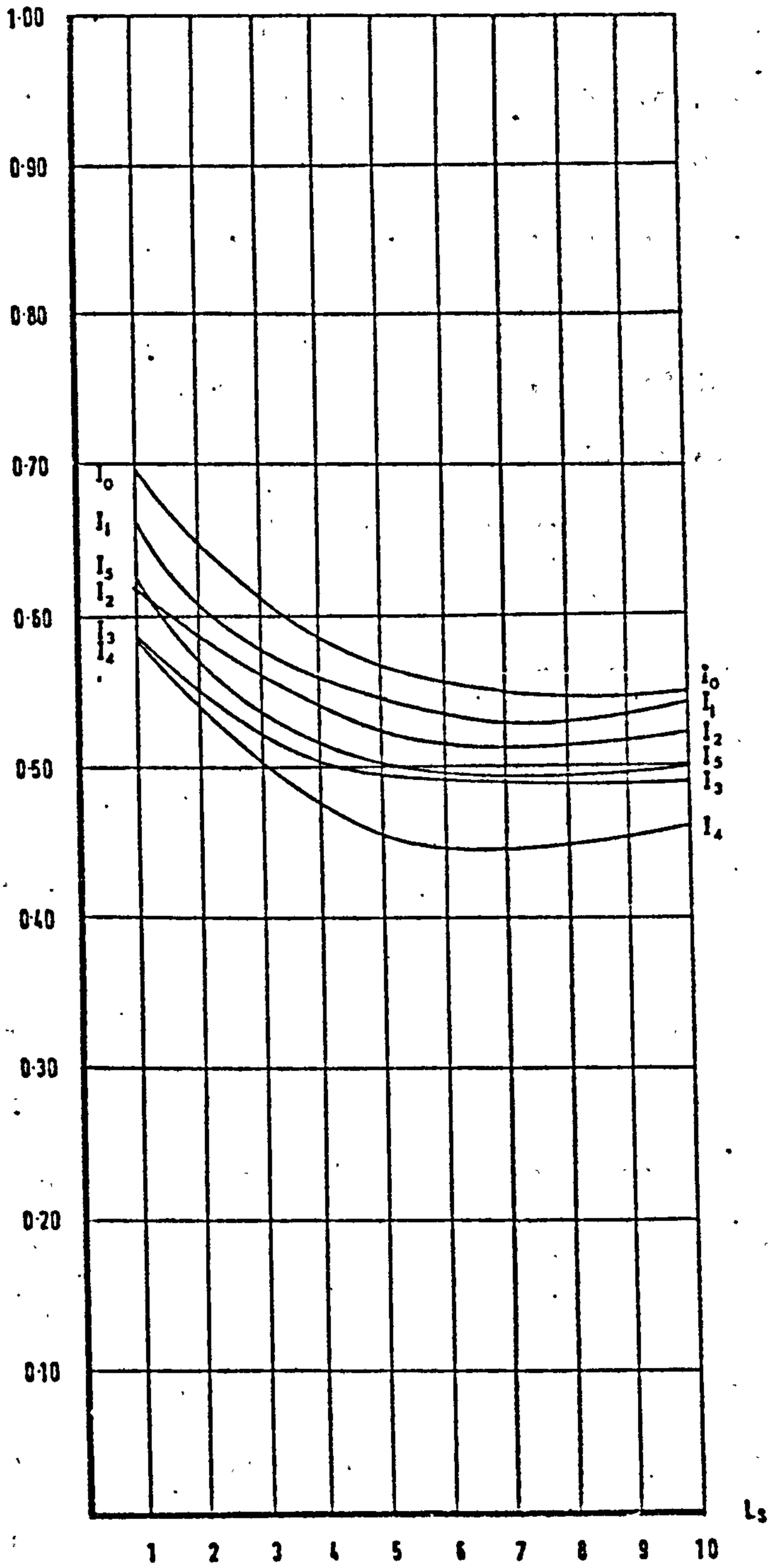


DIAGRAM 4.20 COMPARISON BETWEEN THE DIFFERENT MEASURES OF EXPOSURE AT BLOCK LENGTH 15 FOR DIFFERENT SPACE SIZES

between the highest estimation given by I_0, and the lowest, given by I_4 is the smallest so far - 7 - 9%. All six measures agree on the position of maximum values and minimum values. Maximum values occur at space 1 and minimum values towards the larger spaces. However, some of the measures show earlier positions of minimum values than others. For I_1 the minimum value of exposure begins to occur at space 5 and remains stationary at this value with further increase in space. I_4 shows minimum value at space 8 and remains unchanged for spaces 9 and 10. Between spaces 1 - 3 I_1 and I_5 almost coincide and beyond that they diverge widely, with I_1 having higher values. I_2 and I_5 show the closest values with differences higher at larger and smaller spaces sizes. I_2 has lower values than I_5 which is opposite to the situation in the previous arrangement. I_3 and I_4 show close values at smaller spaces sizes, but they diverge when spacing increases beyond 3. At about spacing 7.5 I_2 and I_3 coincide, but further on I_3 shows slightly higher values.

11.08 Block length 15 shows further differences between the measures of exposure. I_2 and I_5 show more divergent values than in the previous arrangements with I_2 having higher values for spaces greater than 1.5. The measures showing closest values to each other are I_5 and I_3 especially for spaces greater than 5. At space 1, I_3 and I_4 coincide and with increase in spacing they diverge with I_3 showing values approaching those of I_5. As in the previous arrangements, the highest exposure values are shown by I_6 and the lowest by I_4. At space 1, the difference between I_0 and I_1 is the largest, but this difference decreases with increase in spacing. The range in the values of exposure is about 9 - 10%. At this block length the interference between the different measures' values is minimal. All measures agree on the position of the maximum

exposure values, but differ on the position of the minimum values. I_0 shows the minimum to occur at about space 7 and is unchanged by further increase in space. I_4 shows the minimum value at space 6, but it increases towards larger space sizes.

11.09 Diagrams 4.21 - .23 show comparisons between the different measures of exposure at various space sizes for different block lengths.

11.10 Diagram 4.21 shows a comparison between the different measures of exposure at space size 1 for different block lengths. At shorter block lengths the difference in the exposure estimations for the different measures are relatively small, 8 - 10%. This difference increases with increase in block length. At block length 20 the discrepancy is about 18%. The measures show agreement on the positions of maximum and minimum values. Maximum values occur in the block length range 8 - 10 and minimum values at block length 1. At the smaller block lengths, there is a relatively large interference between the different measures, but this disappears as block length increases. The highest values are shown by I_0 and the lowest values by I_4 at block length 1 and block lengths greater than 6. Between block lengths 2 - 6 the lowest values are shown by I_3. I_2 and I_5 show close values for block lengths greater than 11. Between block lengths 2 - 10, I_2 and I_5 are relatively widely diverged and they are closest at block length 1. All measures except I_4 and I_5 have stationary exposure values in the range 17 - 20 of block length. I_4 and I_5 continue to drop in value until block length 20.

11.11 Comparisons between the measures at space size 4 for different block lengths show a greater variation in the range of maximum and minimum values, diagram 4.22. I_0 shows a range of only 3% whereas I_4 and I_5

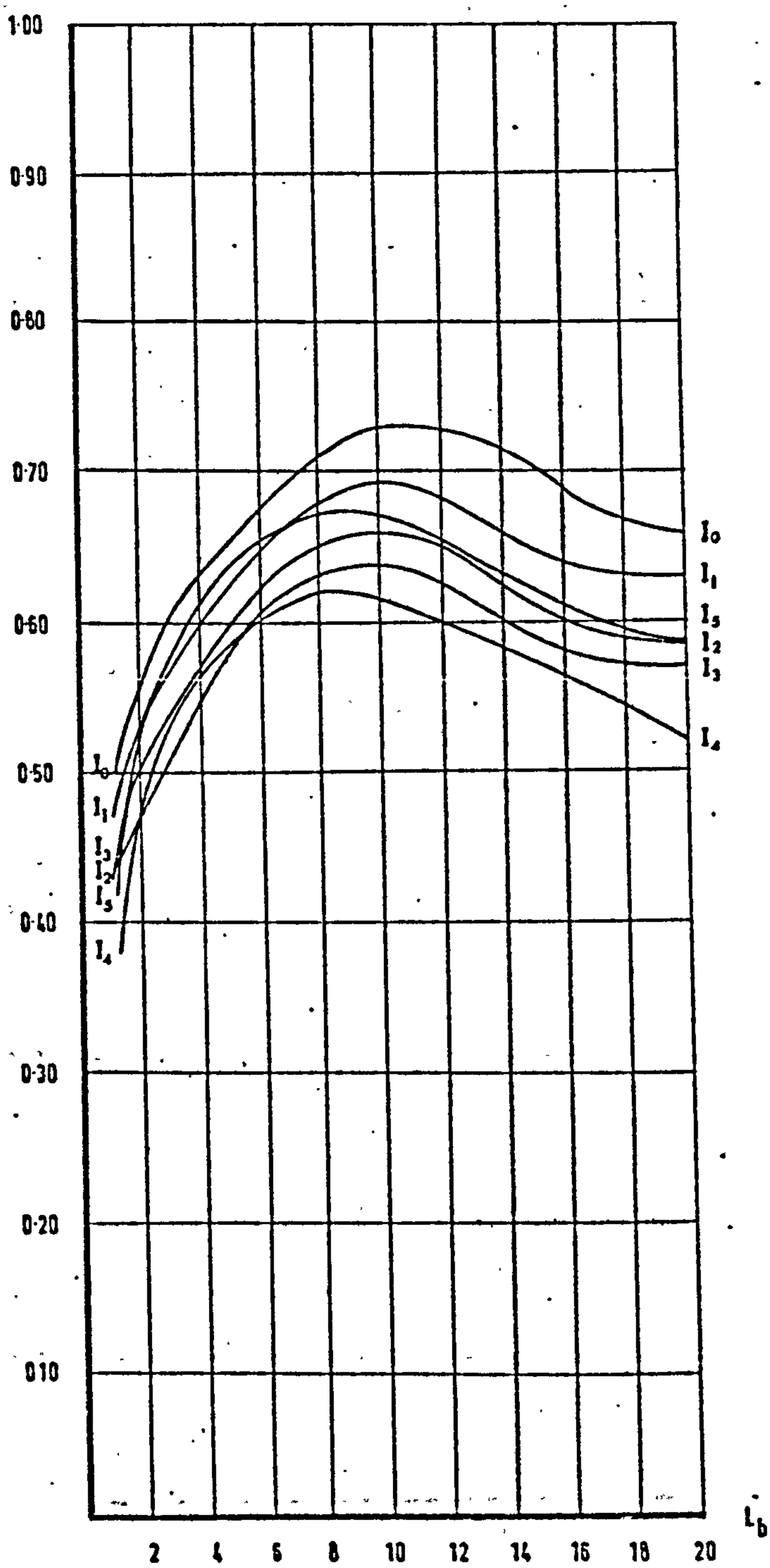


DIAGRAM 4.21 COMPARISON BETWEEN THE DIFFERENT MEASURES OF EXPOSURE AT SPACE SIZE 1 FOR DIFFERENT BLOCK LENGTHS

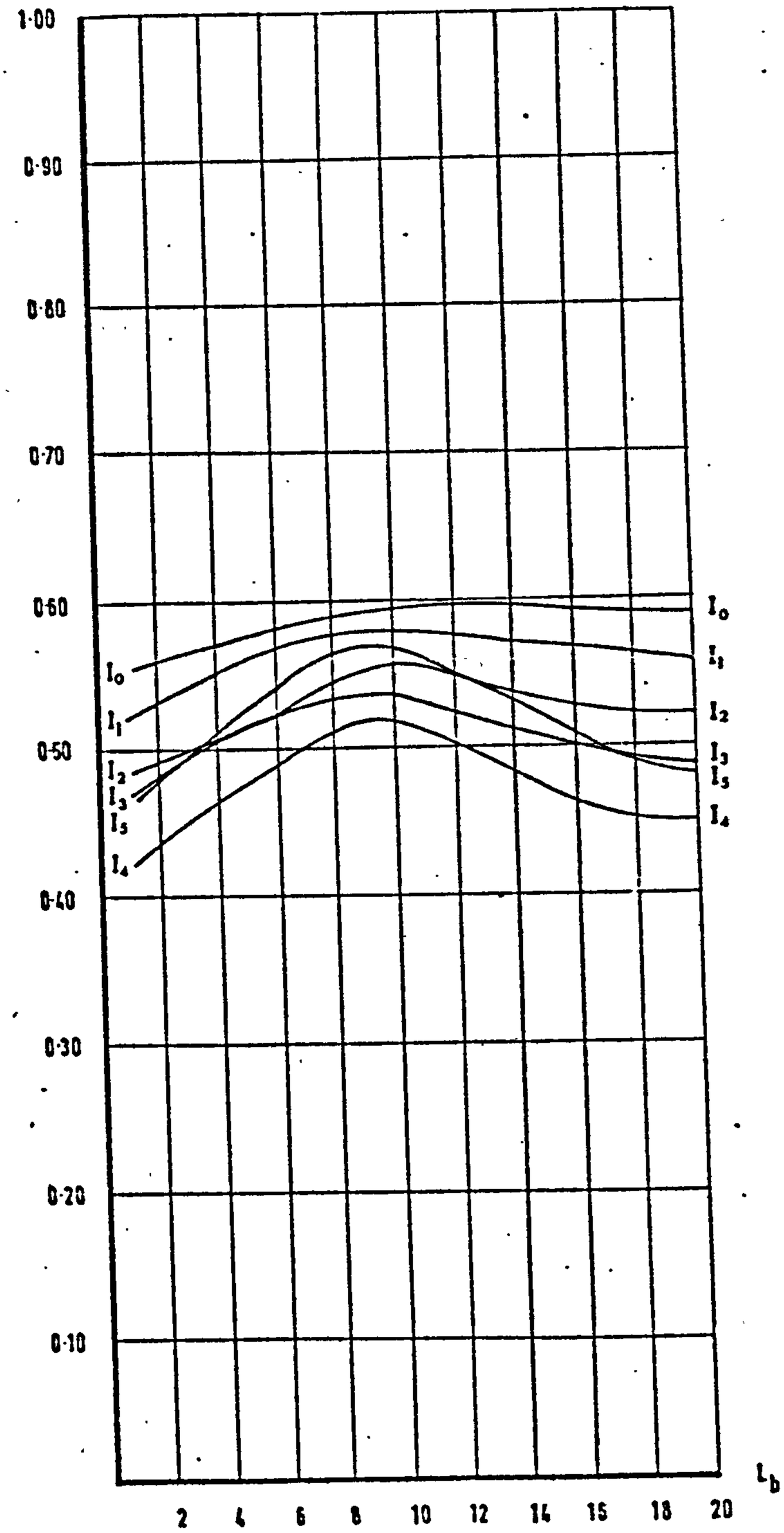


DIAGRAM 4.22 COMPARISON BETWEEN THE DIFFERENT MEASURES OF EXPOSURE AT SPACE SIZE 4 FOR DIFFERENT BLOCK LENGTHS

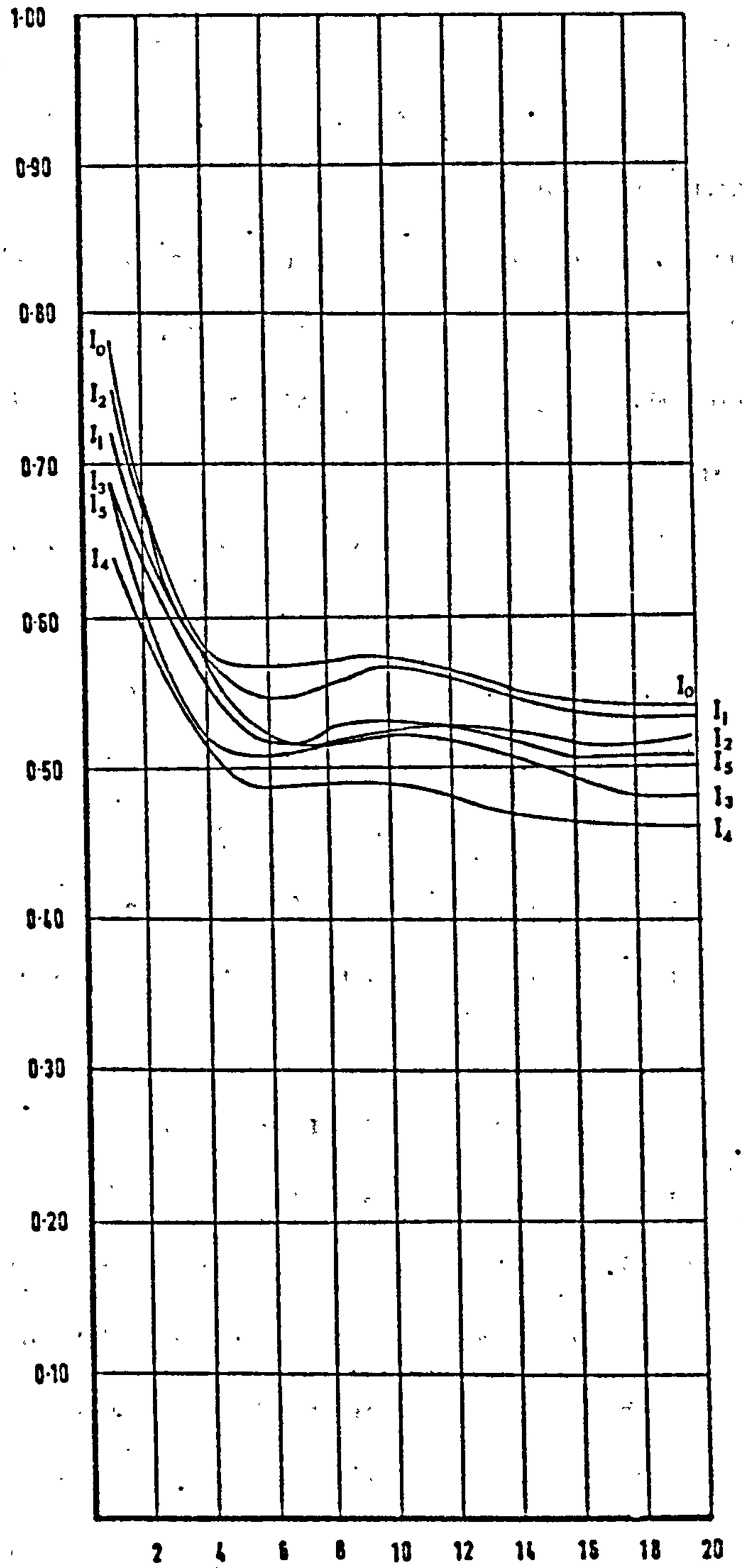


DIAGRAM 4.23 COMPARISON BETWEEN THE DIFFERENT MEASURES OF EXPOSURE AT SPACE SIZE 8 FOR DIFFERENT BLOCK LENGTHS

show a range of about 10%. The variation in exposure with increase in block length also shows wide discrepancies. I_0 increases slowly with increase in block length, until it reaches 0.59 at block length 10, where it remains stationary with further increase in block length. I_5 increases fairly rapidly with block length to reach a maximum value at block length 10, but, opposite to I_4, it decreases with further increase in block length to reach a minimum value at block length 20. I_3 and I_4 increase to a maximum value at block length 10, but decrease with further block length increases to take a stationary value at block length 17. All measures show minimum value positions for this space size at block length 1. Between I_2, I_3 and I_5 there is a large interference with I_5 closest to I_2 for a range of block lengths and closest to I_3 for other block lengths. Between block lengths 1 and 3 I_2 has higher values than I_5. This situation is reversed at block length range 4 - 12. For block lengths greater than 12 the increase in block length increases the difference between I_2 and I_5 with I_2 higher than I_5.

11.12 At larger space sizes, the range in exposure estimations is largest at shorter block lengths and decrease with increase in block length. This is shown for space size 8 in diagram 4.23. I_0 shows the highest values of exposure and the lowest values are shown by I_5. At block length 1 the range between highest and lowest exposure values is about 14%. This range value decreases with increase in block length to about 8% at block length 6 and remains unchanged. At shorter block lengths there is considerable interference between the different measures. All measures show a sharp drop in exposure values when block lengths increase from 1 to 5. Measures I_0 and I_4 give stationary values of exposure between block lengths 5 - 10, before decreasing with further increase in block length. I_1, I_2, I_3 and I_5 values increase slightly after block

length 5 to reach the maximum at block length range 10 - 12. After that their values decrease to minima around block lengths 16 - 17 and remain stationary for larger block lengths. I_0, I_1 and I_2 show relatively close values at shorter block lengths. Similarly do I_3 and I_4. At block length range 7 - 13 I_2, I_3 and I_5 show very close values of exposure but they diverge after that with I_2 having higher values.

SUMMARY OF DIFFERENCES IN EXPOSURE MEASURES

12.01 The exposure values shown by the different measures vary in their values and position in relation to change in form aspects (block length and space size). The measures themselves vary in their behaviour in relation to change in form aspects. These discrepancies were the subject of the above paragraphs of this section, but here they can be summarised as:

a) the value of the exposure index is extremely sensitive to the formulation of the measures. This is shown by the ranges between highest and lowest estimations reaching 18%. Although there are some local variations, exposure measures based on point velocities (I_0, I_1, I_2 and I_3) give higher or lower values of exposure relative to measures of exposure based on an areal velocity component (I_4, I_5 and I_6).

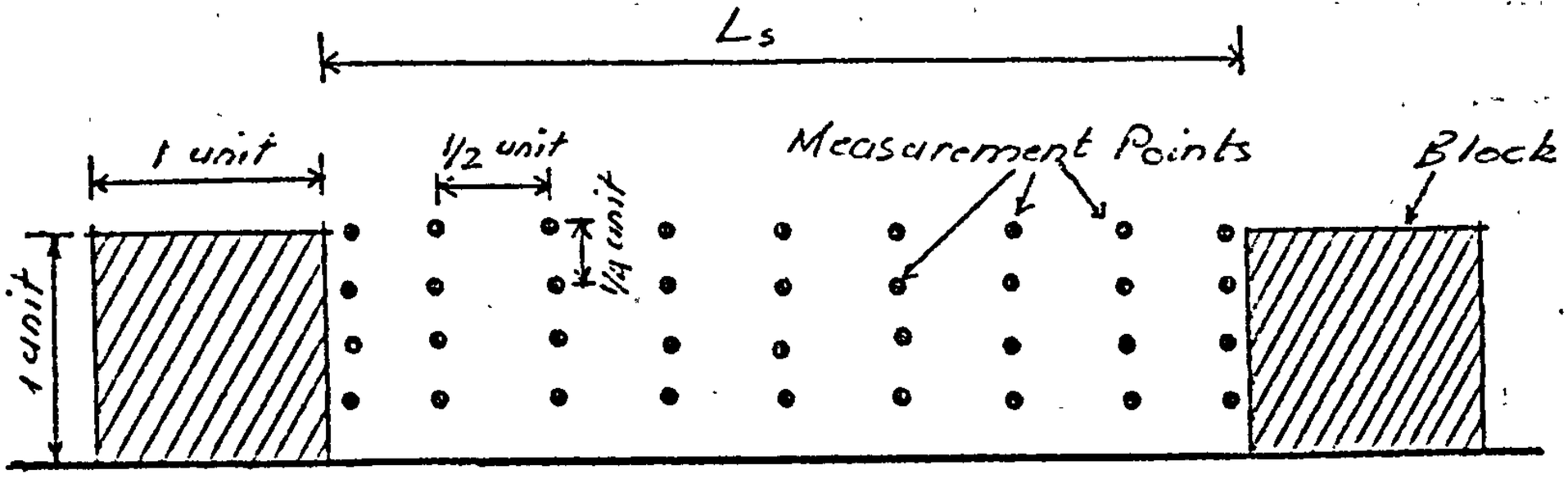
b) the different measures agree on the position of most of the maximum exposure values, but there is a wide discrepancy as to the positions of the minimum and statinnary values. In some cases, there are also differences as to whether stationary values exist according to some measures. These are the most important aspects of the discrepancies in the behaviour of the measures in relation to change in form.

c) the range in values and the rate of change in the measures with form vary widely. While some measures show wide ranges in maximum and minimum values and/or rapid drops or increases in values of exposure with change in form, others show ranges which can be as low as 3% with extremely gentle rates of change. This suggests a discrepancy as to the sensitivity of the different measures to changes in form and that some measures are more responsive to it than others.

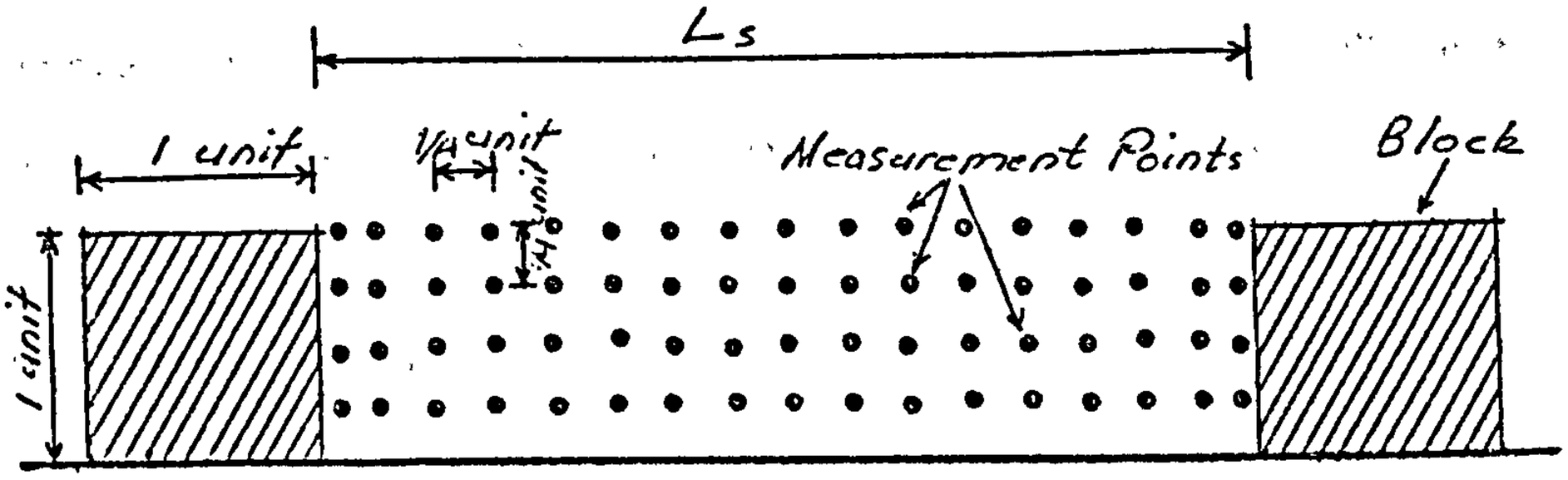
12.02 These discrepancies are clearly significant from the point of view of reliability of the measures. No two measures are sufficiently close in behaviour and/or values to give more credibility to their estimations than others and render them as appropriate measures of exposure. Clearly some measures are less time consuming and less laborious in computation than others, but reliability is a high cost to pay for convenience, especially if the former is not readily ascertainable. It is suggested here that the main factor in these discrepancies has to do with sample size and data structure. In the following section this aspect is investigated by increasing the sample size to study its effect on the estimations of the different exposure measures.

THE EFFECT OF THE SAMPLE SIZE ON THE MEASURES OF EXPOSURE

13.01 Three sample sizes have been used to compute exposure indices. So far, only the exposure estimations of the smallest sample have been discussed. This initial sample is based on a 1-unit grid of measurements. The other two samples are based on 0.5-unit and 0.25-unit grid measurements, but of the same interval of vertical plane of measurements. These two samples are, therefore, twice and four times as large as the



a. GRID DENSITY a



b. GRID DENSITY b

DIAGRAM 4.24: MEASUREMENT POINTS AND GRID DENSITIES FOR LARGER SAMPLES a AND b.

initial sample. Diagram 4.24 shows the points at which the measurements are taken for the two larger samples at space size 4. A further sample, five times the initial sample was used in some cases as a test against further changes in the estimations.

Diagrams 4.25 - 4.28 show the relationship between space size and exposure values computed from different samples using measures I_0, I_1, I_2, I_3 and I_4 for different block lengths. I_{1_a}, I_{2_a}, I_{3_a} and I_{4_a} indicate exposure values computed from sample size a which is twice the initial sample. I_{1_b}, I_{2_b}, I_{3_b}, and I_{4_b} indicate exposure values computed from sample size b which is four times the initial sample. The measures are compared with I_5 which does not change in value with increase in sample size. They converge to the values shown by I_5 as the following sections will reveal. Further comparisons will show that I_5 is the most appropriate measure of exposure.

13.02 The pattern of change in the values of exposure indices with increase in sample size is consistent for the same measure at the different space sizes and block lengths. Therefore, it is sufficient to consider this pattern of change for the different measures at block length 1.

13.03 Diagram 4.25 shows the change in the exposure values of measure I_0 with increase in sample size for block length 1 and different space sizes. This shows that the increase of sample to size a causes a relatively large drop of values. Further drop of values also occurs when the sample increases to size b, but the fall in values is relatively smaller than before. A further increase in the sample size does not significantly affect the values of the exposure which suggests that the exposure values of I_{0_a} show a graph almost parallel to that of I_0 only lower in values. When sample b is used the exposure values drop on in-

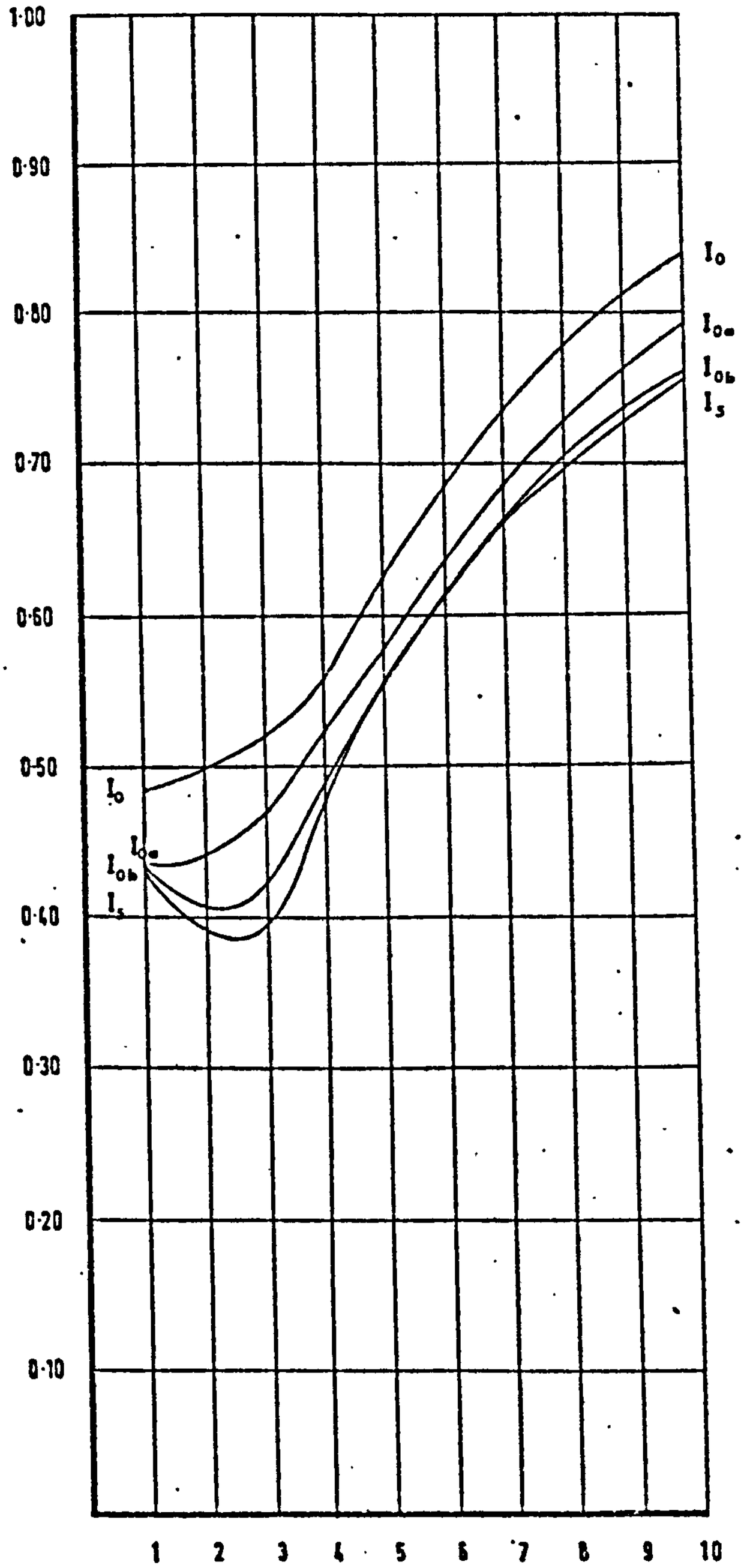


DIAGRAM 4.25 EFFECT OF SAMPLE SIZE ON THE EXPOSURE ESTIMATION OF I_0 IN RELATION TO I_5 (DIFFERENT SPACING FOR BLOCK LENGTH 1)

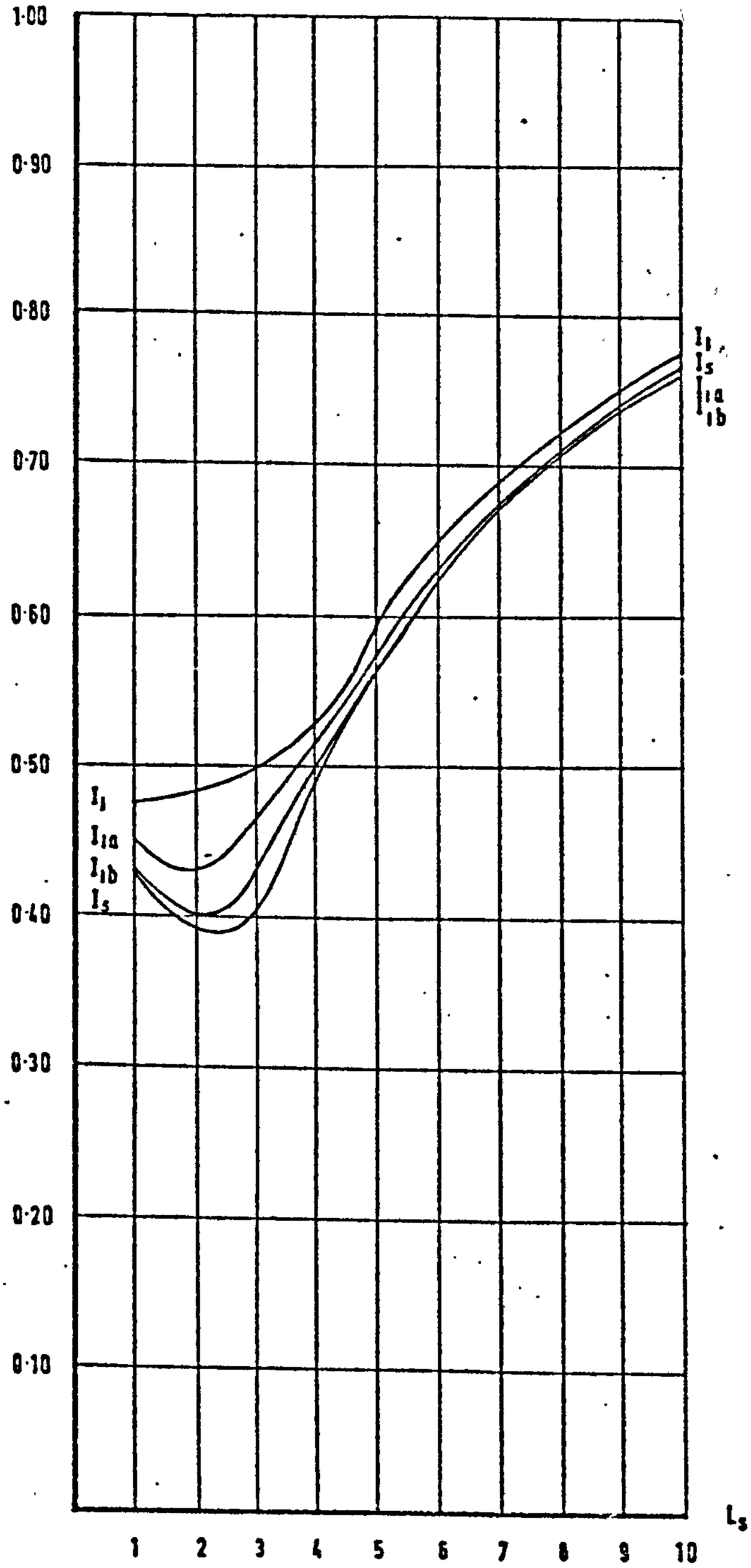


DIAGRAM 4.26 EFFECT OF SAMPLE SIZE ON THE EXPOSURE ESTIMATION OF I_1 IN RELATION TO I_5 (DIFFERENT SPACING FOR BLOCK LENGTH 1)

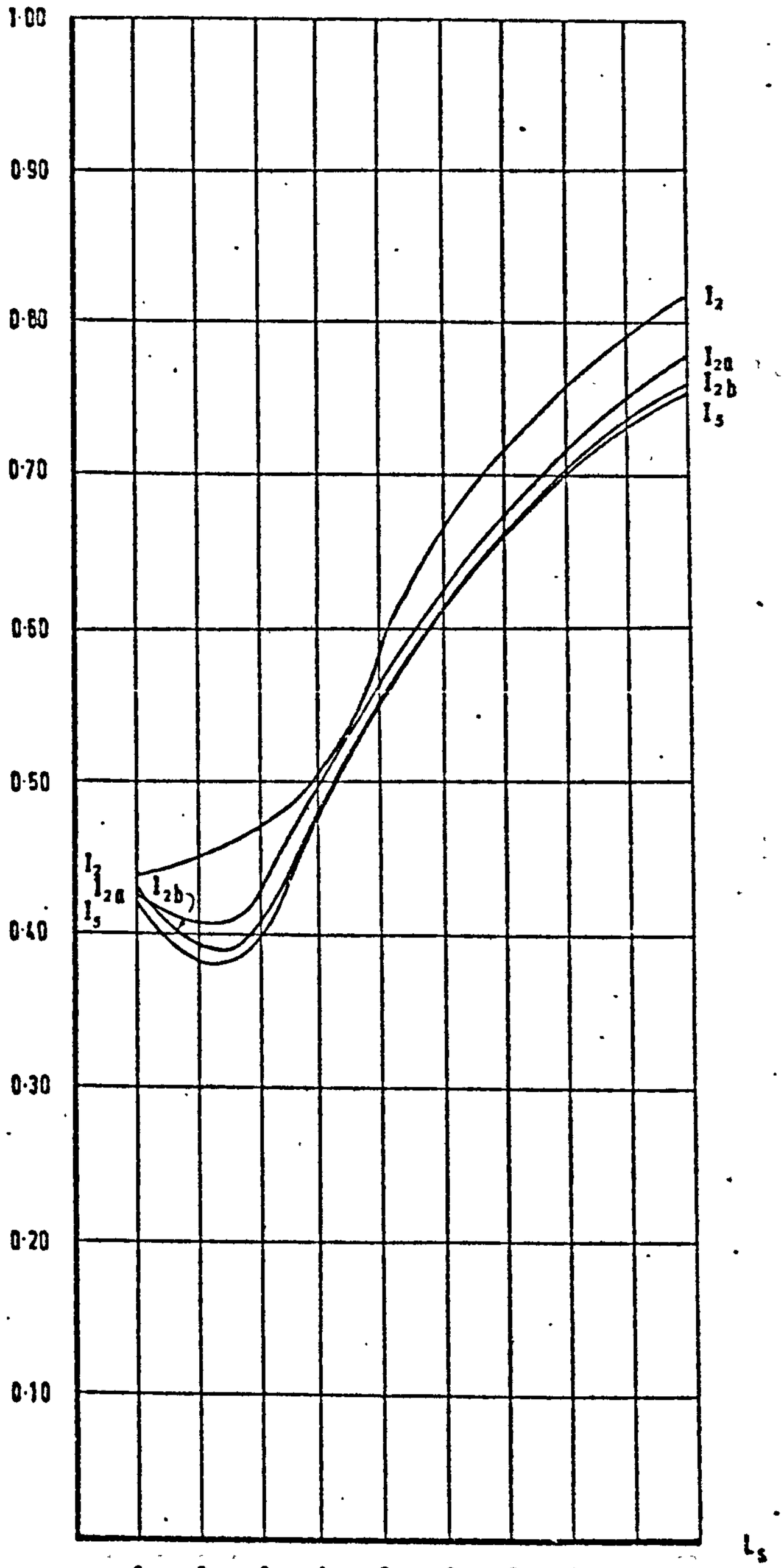


DIAGRAM 4.27 EFFECT OF SAMPLE SIZE ON THE EXPOSURE ESTIMATION OF I_2 IN RELATION TO I_5 (DIFFERENT SPACING FOR BLOCK LENGTH 1)

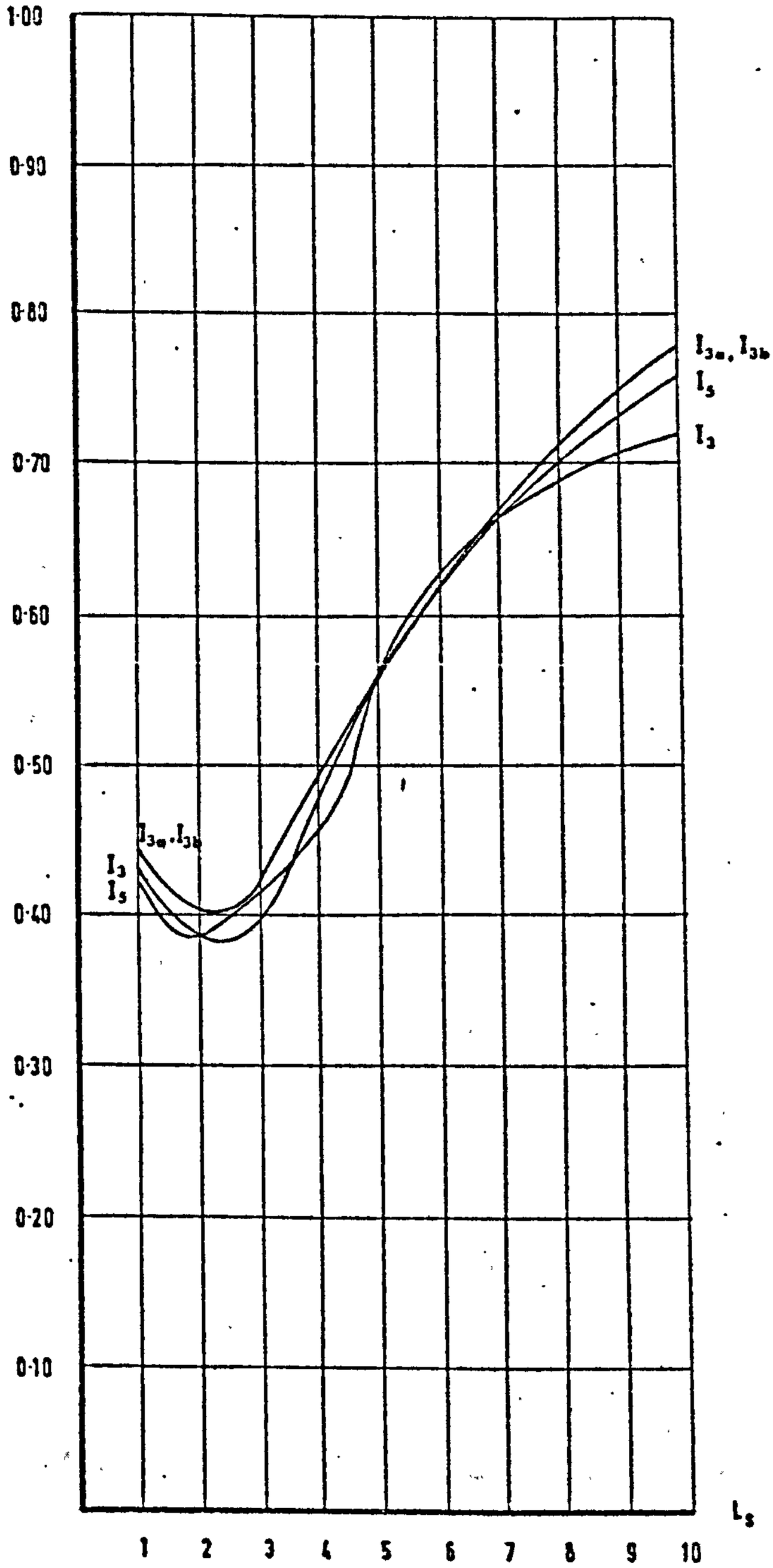


DIAGRAM 4.28 EFFECT OF SAMPLE SIZE ON THE EXPOSURE ESTIMATION OF I_3 IN RELATION TO I_5 (DIFFERENT SPACING FOR BLOCK LENGTH 1)

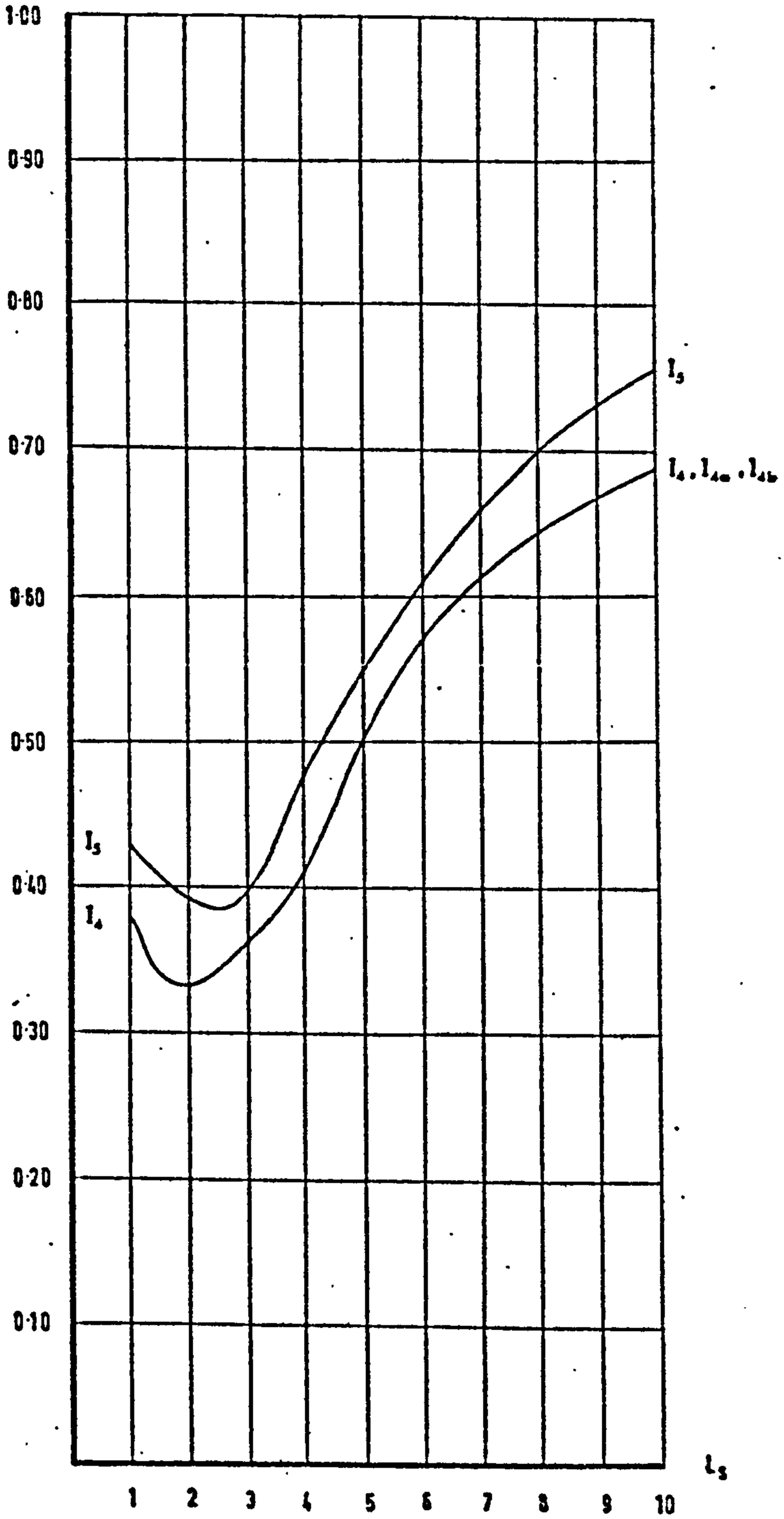


DIAGRAM 4.29 EFFECT OF SAMPLE SIZE ON THE EXPOSURE ESTIMATION OF I_4 IN RELATION TO I_5 (DIFFERENT SPACING FOR BLOCK LENGTH 1)

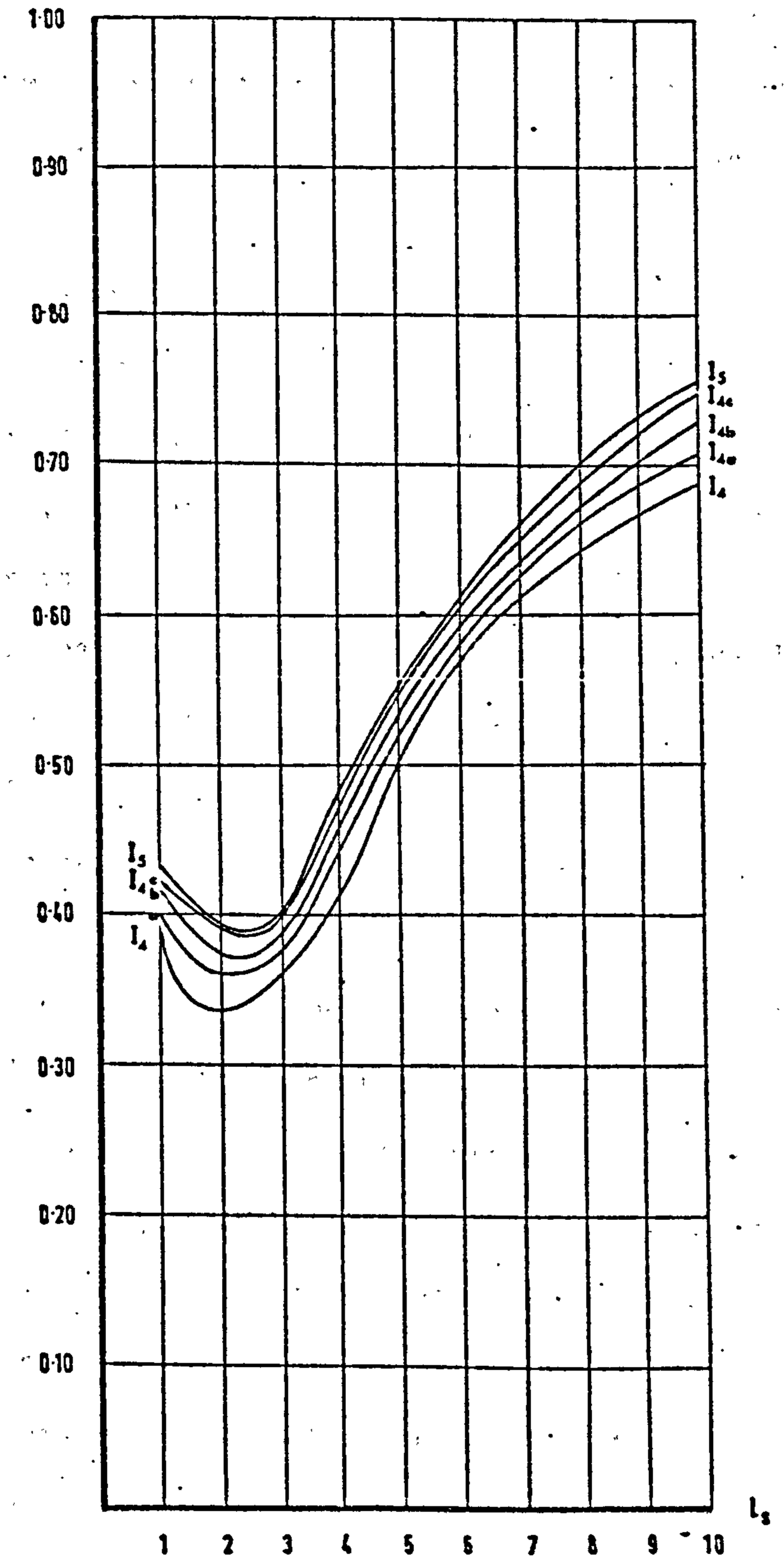


DIAGRAM 4.30 THE EFFECT OF THE INTERVAL OF SPEED CONTOURS ON THE VALUES OF THE EXPOSURE INDEX I_4 IN RELATION TO I_5.
(DIFFERENT SPACING FOR BLOCK LENGTH 1)

creasing the space size between 1 and 2.5. This is a significant departure from the behaviour of I_0 and I_{0_a} for the same space range. Compared with I_5, which has no, or negligible, change with sample size, this behaviour is similar to that of I_5 for the same space range. It can also be seen that I_{0_b} follows closely the values shown by I_5.

13.04 The increase in sample size affects measure I_1 in a slightly different way from I_0 for the same block length, diagram 4.26. In general, the values of the exposure index decrease with the increase in sample size. This decrease, however, is not consistent throughout the range of space sizes. It is relatively large at smaller space sizes, but negligible at larger space sizes. As in the case of measure I_0 the drop in exposure values as a result in increase of the sample size stabilises itself at values nearest to those shown by I_5 and for the larger space sizes the exposure values of I_{1_b} and I_5 almost coincide.

13.05 The effect of the sample size on the exposure indices computed from I_2, diagram 4.27, causes the exposure values to drop and stabilise close to values shown by I_5. The drop is initially large, but relatively small at sample size b. Unlike the previous measures, at sample size a the behaviour of I_{2_a} is such that it decreases between spaces 1 - 2.5. The same behaviour continues at sample b. The change in exposure values as a result of sample size is more pronounced at the two extremes of the space range, i.e., at smaller and larger spaces, but negligible in the intermediate spaces.

13.06 Exposure measure I_3 , in contrast to the previous three measures, increases with the increase in sample size, diagram 4.28. Since I_3 fluctuates with respect to I_5 an increase in sample size stabilises its

position in relation to I_5 . This position is either coinciding with, or slightly higher than I_5 . The change in values, however, is relatively small compared with the previous measures.

13.07 Since I_4 is computed on the same principles as I_5 except for a lower velocity component, the increase in sample size hardly affects it, diagram 4.29. In this it is, therefore, similar to I_5 in remaining virtually unchanged by this type of sample change. It is, however, affected by another type of sample change effected by changes in the speed contours interval. The smaller the interval the closer its values become to I_5. This is shown by diagram 4.30. Three intervals - 7.5%(a), 5%(b) and 2.5%(c) are used to compute I_4.

13.08 The exposure measure I_6 remains close to I_5 and is unaffected by increases in sample size.

13.09 From these results it can be seen that:

a) the sample size is crucial to exposure measures based on computations of point velocity measurements. To have stable and reliable estimations of exposure indices these measures (I_0, I_1, I_2 and I_3) require a sufficiently large sample of measurements.

b) measures of exposure with an areal component of velocity are least affected by the increases in sample size. With relatively small sample sizes, these measures have the advantages of consistency and economy.

c) when computing exposure indices using I_4 the choice of the speed countour interval is important. A large interval with the lower speed value produces low exposure values and high values if the

upper speed contour value is used. An interval of 2.5% gives reasonable values of exposure when compared with those of I_5. But this interval makes computation more laborious and I_4 is, therefore, less suitable than I_5 and I_6.

d) the exposure measures

$$I_5 = \sum_{i=1}^{100} \left[\frac{a_i (V_i + V_{i+10})}{2} \right] \Big/ 100A$$

and

$$I_6 = \sum_{i=1}^{N} \left[\frac{a_i (V_{i_1} + V_{i_2} + V_{i_3})}{3} \right] \Big/ 100A$$

provide reliable measures of exposure with relatively large economies in data requirements. While I_5 is based on a concept requiring legible speed contours, I_6 is more versatile and computations using it can be made directly from point measurements, especially when speed contours are difficult to establish.

CONCLUSIONS

In developing a measure of exposure which satisfies the requirements of consistency, minimal data requirements and sensitivity to change in form, a comparative search into seven possible measures of exposure has shown the following:

1. the different measures show substantial disparities in their estimations of exposure values. These disparities are not consistent throughout the arrangements for which exposure indices were computed. This excludes the possibility of the measures being dependent on the forms for which exposure indices are calculated.

Since the disparities are large (reaching 18% in some cases) it is pertinent in air movement studies to choose reliable measures of exposure.

2. although the different measures are basically not dissimilar in their behaviour with change in form, a substantial number of arrangements have shown disagreements. These disagreements pertain to positions of minimum and stationary values, rates of increase or decrease and tendencies within limited ranges of space size and block length.

3. theoretically, all the measures studied are measures of an average property (the exposure) but they fall into two distinct groups. The first group, based on calculating an exposure index from direct point-speed readings (I_0, I_1, I_2 and I_3) gave relatively high values of exposure for the smallest sample size (based on al-unit measurements). The second group (I_4, I_5 and I_6) based on an areal speed component showed consistently lower values of exposure for the same sample size. This suggests that computations from point speed measurements are more likely to have a strong local bias in their index values. This local bias makes the first group of measures sensitive to sample size and to relieve it relatively large samples are required when applying this family of measures.

4. the effect of the sample size on the measures was studied by increasing the sample to as much as five times the initial sample. Exposure indices were computed using the seven measures from the new samples. This has shown that measures I_0, I_1, I_2 and I_3 are extremely sensitive to sample size compared with I_4, I_5 and I_6 which show no or negligible change with in-

crease in sample size. The nature of the changes in I_0, I_1 I_2 and I_3 as the sample size increases is such that they shift towards I_5, whose values show little or no change and become stabilised at values close to those of I_5. This affirms that measures I_0, I_1, I_2 and I_3 have a strong local bias which has to be counteracted by sufficiently large samples. The other measures avoid this by having an areal speed component amounting to an initial augmentation of the sample by averaging over a large area instead of at isolated points of the measurement grid. The area-based measures are particularly useful because their data requirements are far less than those of the point-based ones by a ratio of 4:1. With the costly and time-consuming measurements and the large disparities associated with small data sizes in the case of point-based exposure measures the values of the area-based exposure measures is very significant.

5. both I_5 and I_6 use interpolation from direct measurements. Although in many cases they can be used interchangeably, I_6 has a greater applicability in situations where patterns of flow are complex and are hard to represent by simple speed contours. This renders the computations using I_5 difficult or impossible and I_6 is therefore a perfect substitute.

6. in the case of I_4 the choice of speed interval is important for reliability of the exposure indices. Intervals of 2.5% are more likely to produce exposure values matching those of I_5 and I_6.

C H A P T E R V

THE DEVELOPMENT OF A MEASURE OF NON-UNIFORMITY

1.00 INTRODUCTION

The exposure measure describes an average property due to change in initial flow conditions as a result of an imposed obstruction. This average property can be misleading as to what happens locally, with respect to the region for which the exposure index is computed. It is reasonable to expect that local values of exposure deviate substantially from the computed value of the exposure index. Depending on the nature of the obstruction and the wind, a flow region under the influence of such an obstruction would show a high degree of uniformity of exposure, i.e., only small or no deviations of local exposure values from that of the average exposure for the whole region, or a low degree of uniformity in which local exposure values deviate widely from the average property. Therefore, it is important in a design context to identify not only the average property defined by the exposure index, but also the average property which defines how and to what extent the local properties deviate from the average properties. This may be achieved by the application of a measure which will be termed the non-uniformity measure. It is expressed as a percentage of the exposure index of the relevant region. The higher the value of the non-uniformity measure the greater the local deviations from the overall exposure index and vice-versa.

PROPERTIES OF THE NON-UNIFORMITY MEASURES

2.01 The purpose of a measure of non-uniformity in wind-built form studies is to express characteristics of the exposure inevitably concealed by the average measure of exposure. The non-uniformity concept can be based on the following considerations:

a) non-uniformity pertaining to a given space in which the local values are expressed as a general property at a given point of time. This can be termed the static non-uniformity.

b) non-uniformity in which local values, or a local value, are expressed as a general property over a period of time. This can be termed the dynamic non-uniformity.

c) non-uniformity concerning a given space over a period of time. This concept can be termed total dynamic non-uniformity.

2.02 This chapter is concerned with the behaviour of certain measures of non-uniformity in relation to wind flow and built form studies. The investigation concentrates on properties of consistency, data structure, economy and sensitivity to form from the particular point of view of wind and built form. Concept a, above, of non-uniformity is used, but the measures are not necessarily restricted to this concept only.

2.03 The statistical measures of dispersion provide a good starting point for the development of a non-uniformity measure. Since they show, as will be discussed in the following sections, substantial disparities in values, behaviour and sensitivity to change in form, it is important to sift through these potential measures to adapt the most appropriate non-uniformity measure in the context of wind flow and built form, in terms of data requirements (size and organisation), behaviour and sensitivity to changes in form.

2.04 As in the case of the exposure measures, the measures of non-uniformity have to cope with problems of data (velocity measurements) pertaining to form arrangements which invariably produce different gradients between velocity values in a given grid of measurements (chapter IV, para. 2.01)

In chapter IV three different approaches were suggested to deal with this problem in the development of an exposure measure. The same applies in the development of a non-uniformity measure (chapter IV, para. 2.01).

THE STATISTICAL MEASURES OF DISPERSION

3.01 The statistical measures of dispersion determine the degree to which a given set of numerical data tend to spread about an average value of the set. Such measures in common use are the range, mean deviation, semi inter-quartile range, the 10 - 90 percentile range and the standard deviation.[47]

3.02 The range of a set of numbers is the difference between the largest and the smallest numbers of the set.

3.03 The mean deviation, also known as the average deviation, of a set of numbers, x , x , ... x_n is defined by

$$M.D. = \frac{\sum_{i=1}^{n} |x_j - \bar{x}|}{n}$$

where $\bar{x}$ is the arithmetical mean of the numbers and $|x_j - \bar{x}|$ is the absolute value of the deviation of x_j from $\bar{x}$.

3.04 The semi inter-quartile range of a set of data is

$$Q = \frac{Q_3 - Q_1}{2}$$

where Q_1 and Q_3 are the first and third quartiles of the data. A median divides the data into two equal parts but data can be divided into three or more equal parts. The values which divide the data into four equal parts are called quartiles and they are a set of three values denoted as Q_1, Q_2

and Q_3. In this case Q_2 corresponds to the median.

3.05 The values which divide the data into hundred equal parts are called percentiles. The 50th percentile corresponds to the median. The 25th and 75th percentiles correspond to the first quartile Q_1 and the third quartile Q_3 respectively. The 10 - 90 percentile range is a measure of dispersion defined by:

$$10 - 90 \text{ percentile range} = P_{90} - P_{10}$$

where P_{10} and P_{90} are the 10th and 90th percentiles respectively.

3.06 The standard deviations of a set of numbers $x_1, x_2, \ldots x_n$ is denoted as s and defined by:

$$s = \sqrt{\frac{\sum_{j=1}^{n} (x_j - \bar{x})^2}{n}}$$

where x represents deviations of each of the numbers x_j from the mean $\bar{x}$. Since s is the root mean square of the deviations from the mean it is also called the root mean square deviation.

3.07 The standard deviation can further be defined as

$$s = \sqrt{\frac{\sum_{j=1}^{n} (x_j - a)^2}{n}}$$

where a is an average besides the arithmetical mean. The minimum value for such standard deviations is that for which $a = \bar{x}$.

3.08 The above measures show simply how the data varies from a measure of average. The actual variation or dispersion as determined from the standard deviation or other measures of dispersion is called the absolute dispersion. To measure the dispersion in relation to the av-

erage from which the data varies, a relative dispersion measure is defined as:

$$\text{Relative Dispersion} = \frac{\text{Absolute Dispersion}}{\text{Average}}$$

This measure is particularly useful in comparative studies, hence its potential in design-oriented measures of wind.

THE DEVELOPMENT OF A NON-UNIFORMITY MEASURE

4.01 In the following sections, the non-uniformity of exposures will be computed using measures based on the statistical measures of dispersion. Non-uniformity indices will be calculated for a central vertical plane between sets of two parallel blocks of varying lengths and spacing. The blocks are placed with their length normal to the flow axis.

4.02 To develop the non-uniformity measure, a comparison is first made between the values yielded by the different formulations as non-uniformity indices are computed for thedifferent arrangements. Since there are two main types of data structures, point-based and area-based, the effect of the type of data structure on the values and behaviour of the non-uniformity measures will be investigated. As in the case of developing an exposure measure, the effect of the sample size on the non-uniformity measures is also studied.

NON-UNIFORMITY MEASURES U_1, U_2, U_3 AND U_4

5.01 In the following sections four possible measures of non-uniformity are studied. These are U_1, U_2, U_3 and U_4. The first measure U_1 can be stated as:

$$U = \left[\left(\frac{\sum_{i=1}^{N} |V_i - I|}{N} \right) / I \right] \times 100$$

where $_i$ is a speed at a point.

I is average exposure (I)

N is the sample size - total number of readings.

5.02 For an area-based measure of exposure, the non-uniformity measure U_I' can be written as:

$$U_I' = \left[\left(\frac{\sum_{i=1}^{N} a_i(|V_i - I|)}{A} \right) / I \right] \times 100$$

where V_i is the representative velocity of the local area a_i.

a_i is the area bounded by the two speed contours.

N is the number of local areas.

A is area of the relevant plane of measurements.

I Average exposure (I_5).

5.03 The second non-uniformity measure U_2, is stated as:

$$U_2 = \left[\left(\frac{Q_3 - Q_1}{2} \right) / I \right] \times 100$$

where Q_1 and Q_3 are the first and third quartiles of the grouped data - values of speed at points or local area exposure values. I is the value of the exposure index of the arrangement. I is an exposure measure which is either point-based or area-based.

5.04 Based on a finer division of grouped data, the third non-uniformity measure is taken as its percentile range and is stated as:

$$U_3 = [(P_{90} - P_{10})] \times 100$$

where P_{90} and P_{10} are respectively the ninetieth and the tenth percentiles of grouped data. I is the value of the exposure index for the arrangement. As before, it can be either point-based or area-based.

5.05 The fourth measure of non-uniformity, U_4, is based on the statistic standard deviation. It is stated as:

$$U_4 = \left[\left(\sqrt{\frac{\sum_{i=1}^{N} (V_i - I)^2}{N}}\right) / I\right] \times 100$$

where V_i is the exposure value of point i, N is the total number of measurement points and I is a point-based exposure measure for the arrangement (I_1)

5.06 For area-based data, the fourth non-uniformity measure can be stated as:

$$U_4' = \left[\left(\sqrt{\frac{\sum_{i=1}^{N} a_i (V_i - I)^2}{A}}\right) / I\right] \times 100$$

where V_i is the representative velocity of local area, I is an area-based exposure index value (I_5), a is the local area value, N is the number of all local areas and A is the overall area of the measurement plane.

5.07 In all arrangements, the non-uniformity index is given as a percentage of the relevant exposure values. Where the point exposure values or representative velocities of local areas are given as a percentage of the free flow it is necessary to divide by 100 to bring these values to the same base as the exposure index. This is to be done before computations begin.

5.08 In the following sections non-uniformity indices are discussed for a

set of arrangements consisting of the twenty block lengths range and the ten space sizes. In sections 6.00 - 8.00 the non-uniformity indices from U_1, U_2, U_3 and U_4 are computed from data based on point measurements. The differences in estimations among the measures are studied and the effect of the sample size on these measures is investigated. Sections 13.00 - 17.00 are a study of the non-uniformity indices computed from area-based data and the measures of non-uniformity are symbolised by U_1', U_2', U_3' and U_4' for this type of data base. A further study compares the non-uniformity indices computed from the two types of data. These investigations lead to the choice of a suitable measure of non-uniformity and a suitable data base organisation. The main criteria for a good measure will be:

a) that it is economic in its data requirements,

b) that changes in sample size do not substantially affect its estimation of the value of the non-uniformity index, and

c) that it is relatively sensitive to changes in form.

Discussion of the results in the following sections centres on these aspects.

COMPUTATIONS OF NON-UNIFORMITY INDICES FROM EXPERIMENTAL DATA USING DIFFERENT MEASURES (POINT-BASED DATA)

6.00 Non-uniformity measure U_1:

6.01 Diagram 5.01 shows the relationship between U_1 and space size for different block lengths. The increase in space size causes a drop in U_1 for the space range 1 - 5 for all block lengths. U_1 increases slightly towards space 10. The highest value of U_1, about 19%, occurs at block length 10 for space 1. The lowest value is shown by block 15 at space 5. The decrease in U_1 with increase in spacing is relatively gentle for most block lengths. Block length 15, however, shows a relatively sharp drop towards its minimum U_1 value at space 5.

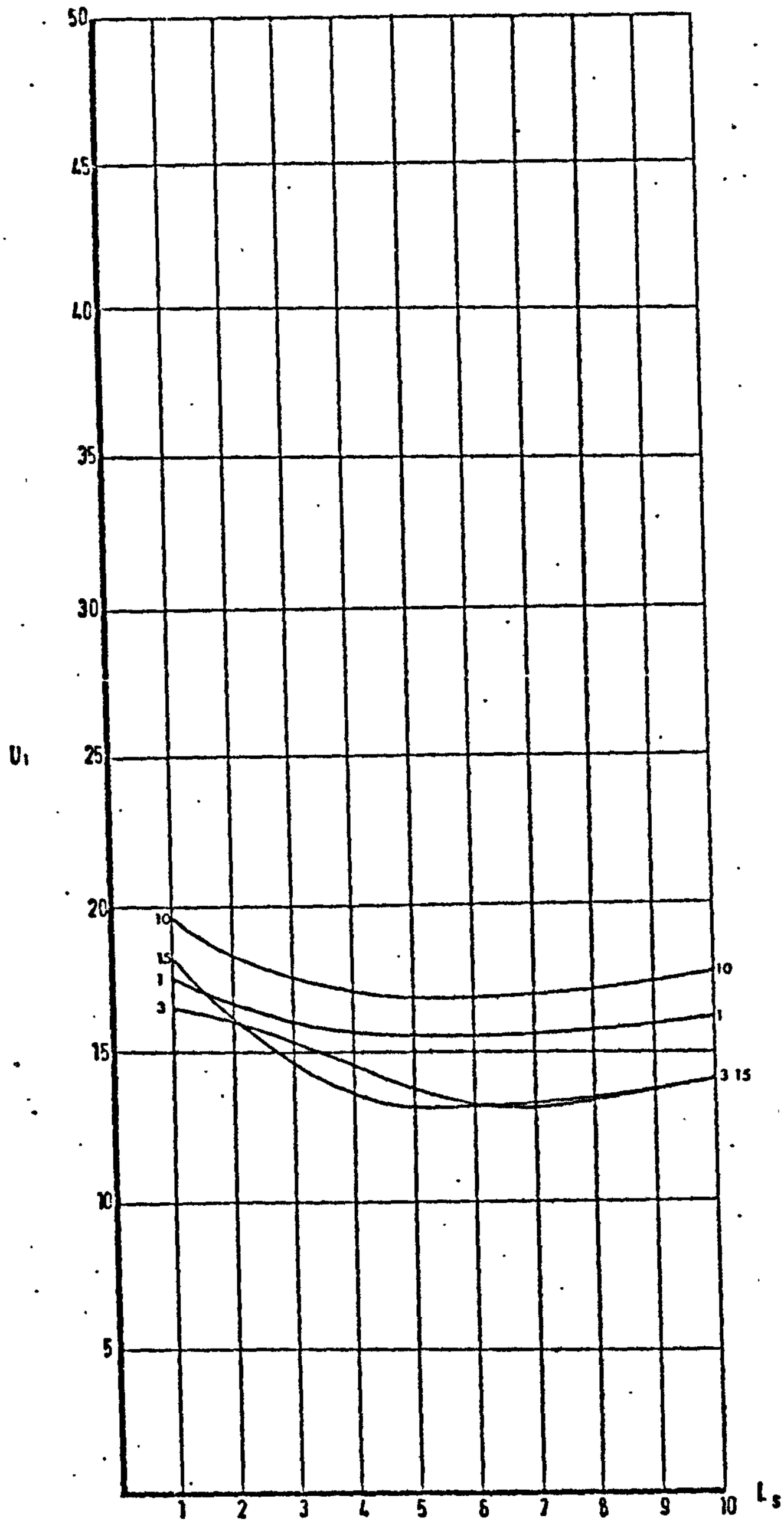


DIAGRAM 5.01: RELATIONSHIP - BETWEEN NON-UNIFORMITY MEASURE U_1 AND SPACING SIZE FOR DIFFERENT BLOCK LENGTHS

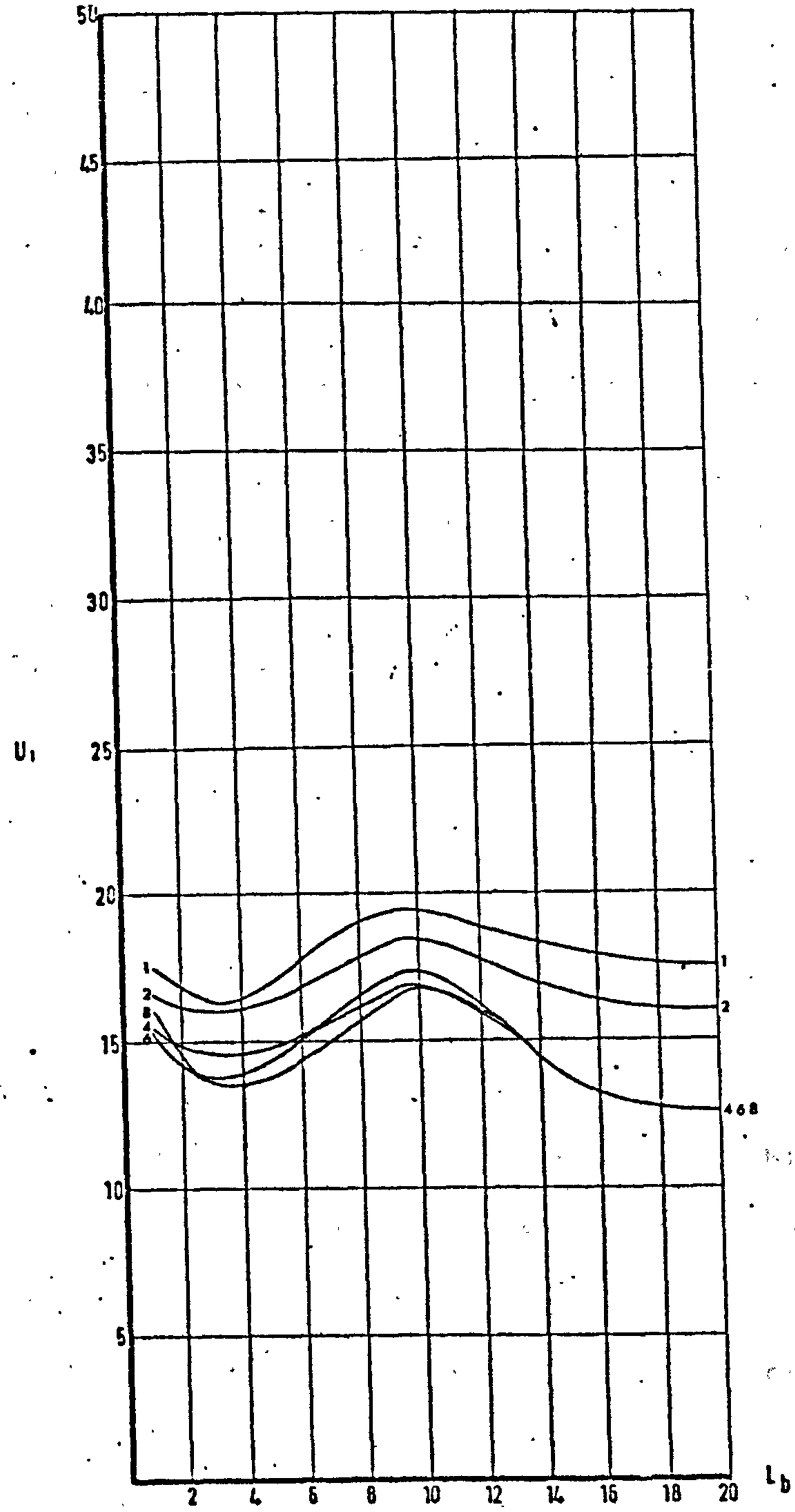


DIAGRAM 5.02: RELATIONSHIP BETWEEN NON-UNIFORMITY MEASURE U_1 AND BLOCK LENGTH FOR DIFFERENT SPACE SIZES

6.02 The relationship between U_1 and block length for different space sizes is shown in diagram 5.02. The general pattern of change is such that there is an initial drop in U_1 between block lengths 1 - 3, an increase towards block length 10 and a further drop towards block length 20. The decrease in U_1 beyond block length 10 is relatively rapid, but it slows down between block lengths 15 - 20. For some space sizes there is hardly any change in U_1 values beyond block length 15. The highest values of U_1 are shown at space size 1 where U_1 value is just below 20% at block length 10. Larger spaces show close values of U_1 as the block length increases. At block length 13 the values of U_1 for spaces 4, 6 and 8 coincide and remain unchanged with further increase in block length. Comparison between the values of U_1 for spaces 4 and 8 shows that at block length 1 space 8 has higher U_1 values, lower values between block lengths 3 - 6 and higher values between block lengths 6 - 13. U_1 values for space 8 are generally higher than those for space 6 at this range of block lengths.

7.00 Non-uniformity Measure U_2:

7.01 The relationship between U_2 and spacing for different block lengths is shown in diagram 5.03. This measure shows generally lower values and a smaller range than U_1. In the space range 1 - 5 U_2 shows a decrease in values with block length 10. Decrease in U_2 values is also shown between spaces 1 - 7 for block length 3 and between spaces 1 - 4 for block length 15. Block length 1 shows a decrease in U_2 with increase in space size falling to a minimum value at space 5 and remaining at it until space 10. With further increase in space, U_2 increases beyond the minimum value for all block lengths except block length 1. The changes in U_2 values with space are gentle, especially at larger space sizes. At block length 15, however, there is a steep drop in U_2 when

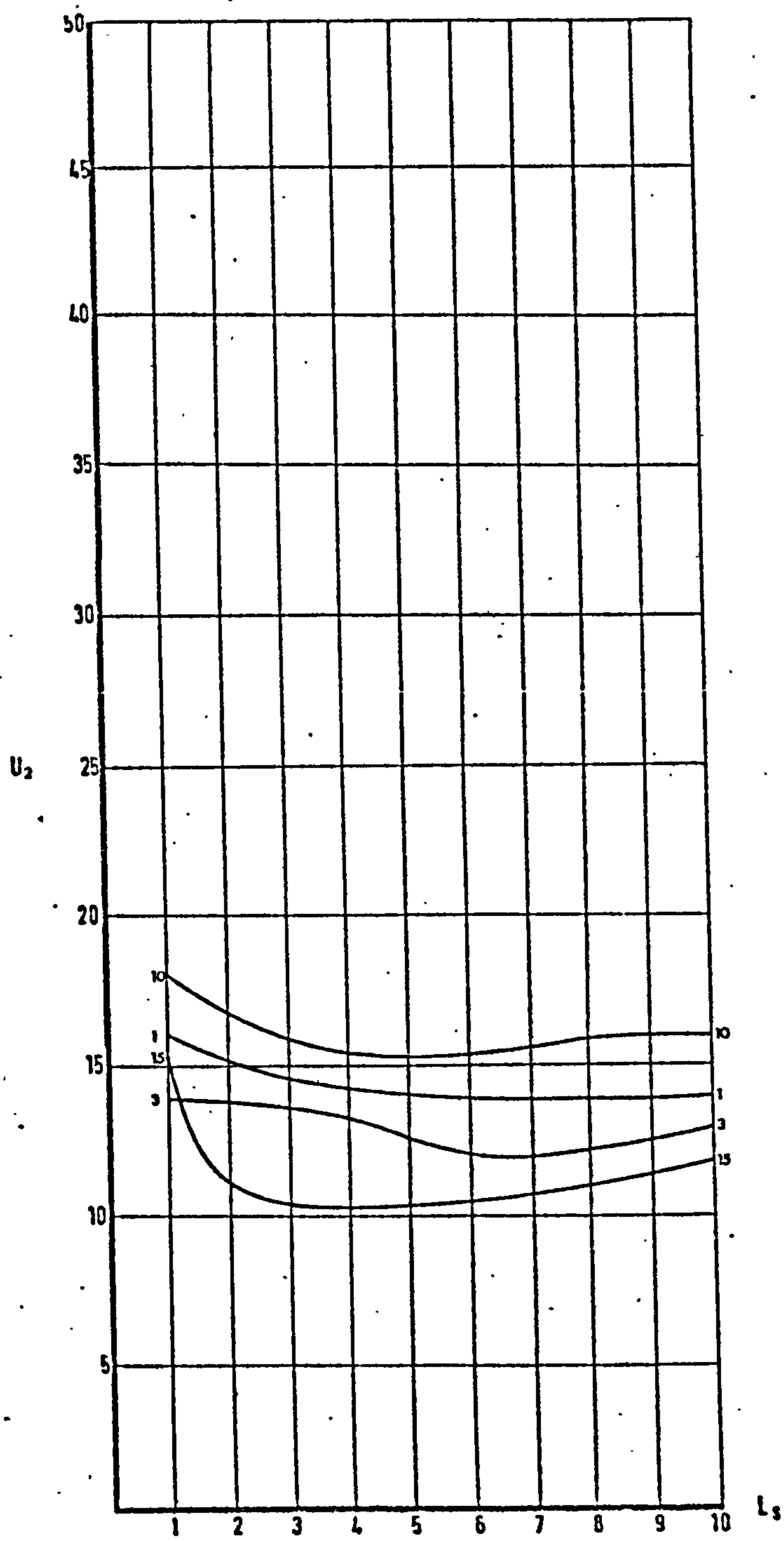


DIAGRAM 5.03: RELATIONSHIP BETWEEN NON-UNIFORMITY MEASURE U_2 AND SPACE SIZE FOR DIFFERENT BLOCK LENGTHS

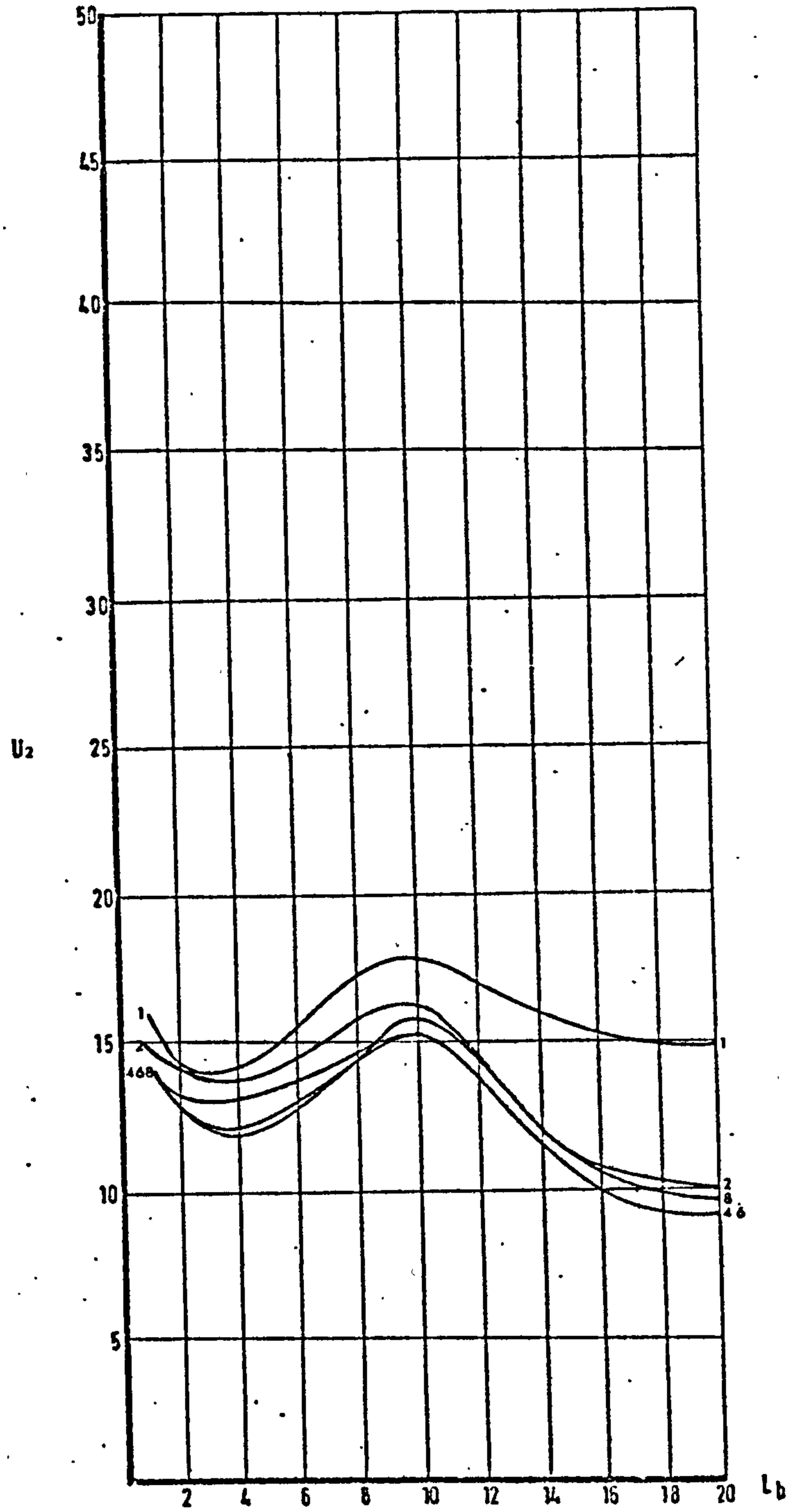


DIAGRAM 5.04: RELATIONSHIP BETWEEN NON-UNIFORMITY MEASURE U_2 AND BLOCK LENGTH FOR DIFFERENT SPACE SIZES

spacing is increased from 1 to 2.

7.02 The change in U_2 with increase in block length for different space sizes is shown in diagram 5.04. The different spacings show the same behaviour in U_2 with increase in block length: an initial fall, an increase and finally another fall in values. The highest values of U_2 are shown at spacing 1 with a maximum of 18% at block length 10. The lowest value is 9% shown at space sizes 4 and 6 at block length 20. The increase in U_2 between block lengths 4 and 10 and the subsequent decrease are relatively steep. At block length 15, however, the change in U_2 values becomes slow and in some cases U_2 remains unchanged with block length increase beyond 15. There is a large interference in the values of U_2 for larger spacings and the differences in their U_2 values becomes relatively narrow beyond block length 10.

8.00 Non-Uniformity Measure U_3:

8.01 U_3 is the third non-uniformity measure and its relationship to space size for different block lengths is shown in diagram 5.05. The measure shows ranges comparable to those shown by U_1 at the smaller space sizes and to those shown by U_2 at the larger space sizes. However, it shows widely different values when taking individual block lengths, e.g., the highest value is shown by block length 15 at space 1, whereas this value is shown by block length 10 in the previous measures. U_3, however, agrees with the previous measures in that its values decrease with increase in space size. This decrease continues to a minimum value at spaces 5 - 6 for block length 3 - 15 before the value of U_3 increases with further increase in spacing. For block lengths 1 and 10 U_3 reaches stationary values at spaces 6 - 10.

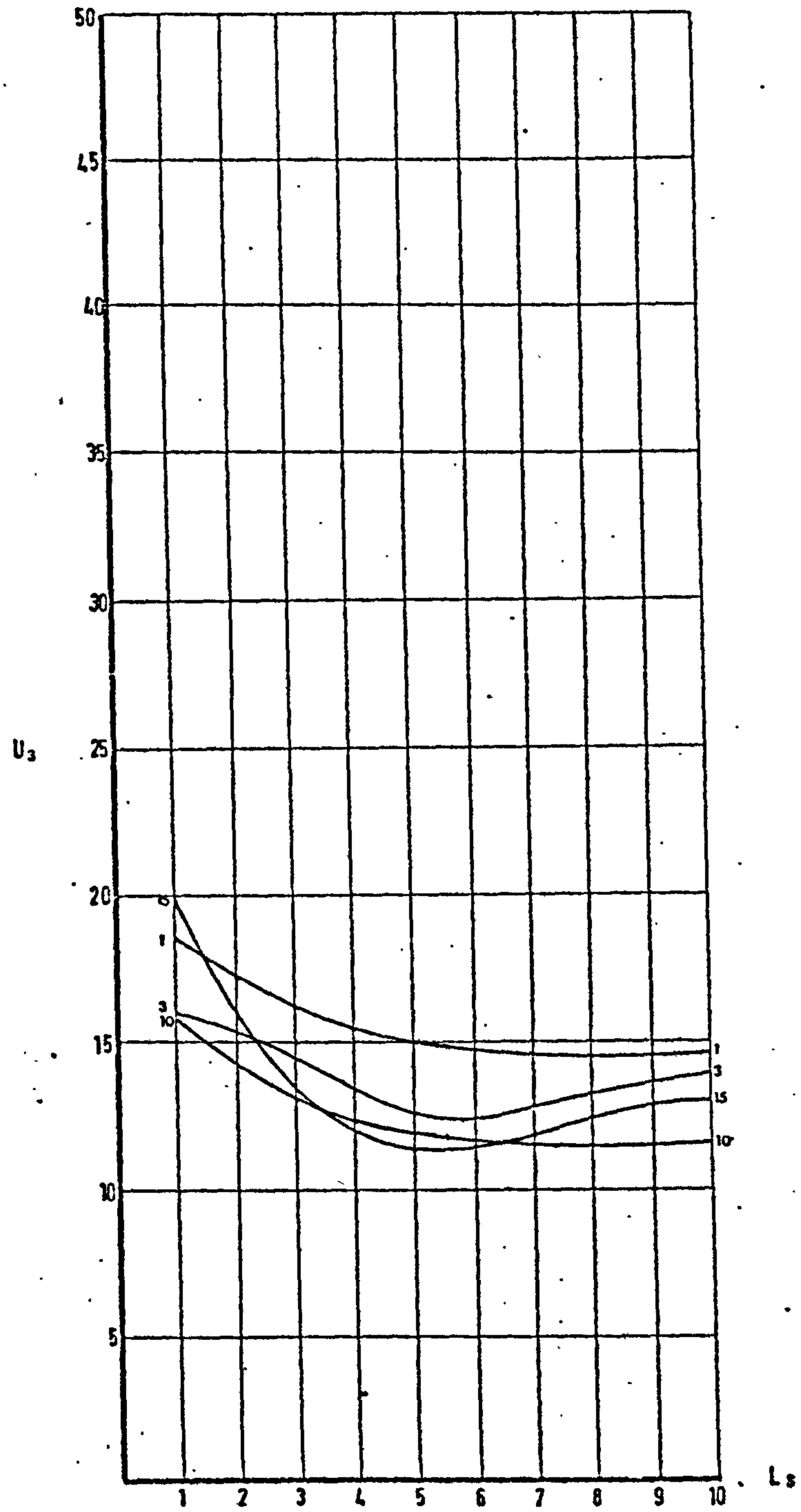


DIAGRAM 5.05: RELATIONSHIP BETWEEN NON-UNIFORMITY MEASURE U_3 AND SPACE SIZES FOR DIFFERENT BLOCK LENGTHS

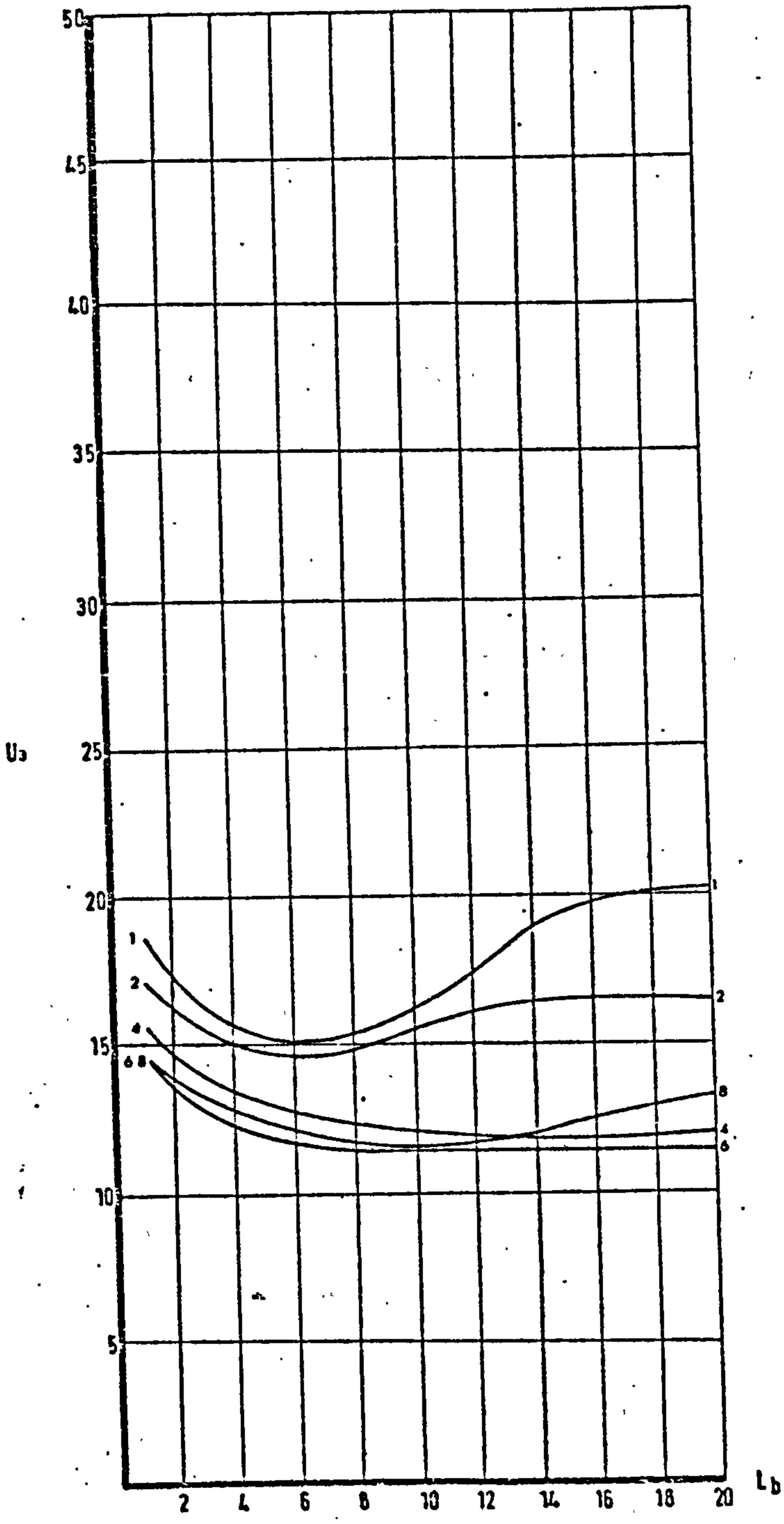


DIAGRAM 5.06: RELATIONSHIP BETWEEN NON-UNIFORMITY MEASURE U_3 AND BLOCK LENGTH FOR DIFFERENT SPACE SIZES

8.02 The change in U_3 with block length shows a different pattern from the previous two measures, diagram 5.06. For space size 1, U_3 decreases with increase in block length to a minimum at block length 6. With further increase in block length U_3 increases until block length 16 and it remains unchanged with further increase. The same pattern of change is shown for spacing 2, except that U_3 maintains a stationary value from block length 13 to 20. For space sizes 4 and 6 there is a steady drop in U_3 values between block lengths 1 - 8, but values of U_3 remain stationary with further increase in block length. The increase in block length at space 8 reduces the value of U_3 to a minimum at block length 10 before it begins to increase beyond this block length. The values of U_3 at spacing 8 are higher than those at spacing 6. They are also higher than those at space size 4 for the block length range 14 - 20. The values of U_3 are relatively close in the space range 4 - 10.

9.00 Non-Uniformity Measure U_4:

9.01 Diagram 5.07 shows the relationship between U_4 and space size for different block lengths. U_4 has much higher values than any of the previous measures of non-uniformity and shows greater sensitivity to change in form. The highest values of U_4 occur at smaller spaces and the lowest values occur at larger spaces and medium spaces. The change in U_4 values is less remarkable at block length 1, where the maximum value, occurring at space 1, is 24% and the minimum value, occurring at space range 5 - 10, is 21%. This is a contrast to what happens at larger block lengths - at block length 15, the maximum value of U_4 occurring at space 1, is just below 26% and the lowest value is just over 14%, occurring at space 5. There are three patterns of change in U_4 in relation to space size and block length. For block length 1, the increase in spacing lowers

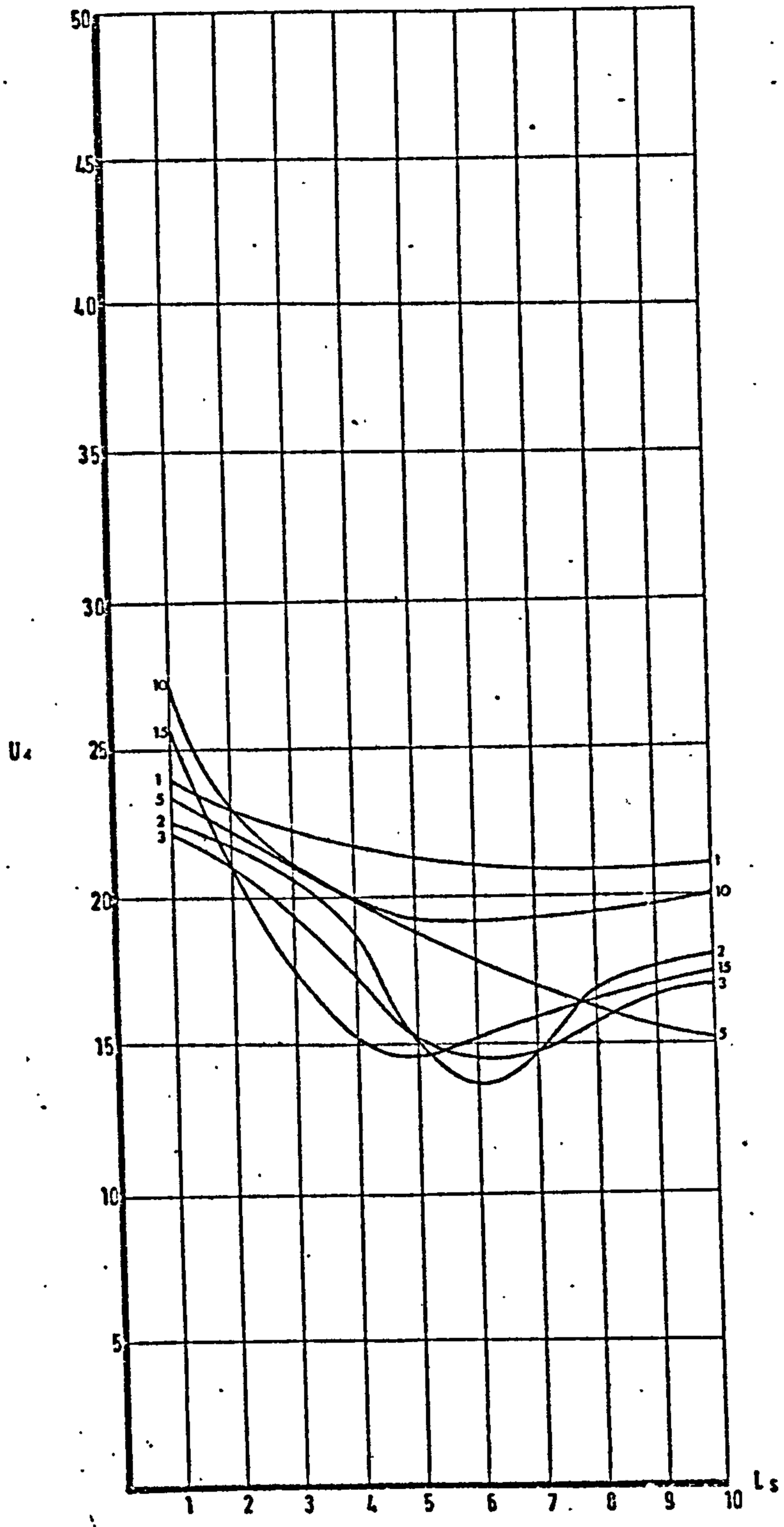


DIAGRAM 5.07: RELATIONSHIP BETWEEN NON-UNIFORMITY MEASURE U_4 AND SPACE SIZE FOR DIFFERENT BLOCK LENGTHS

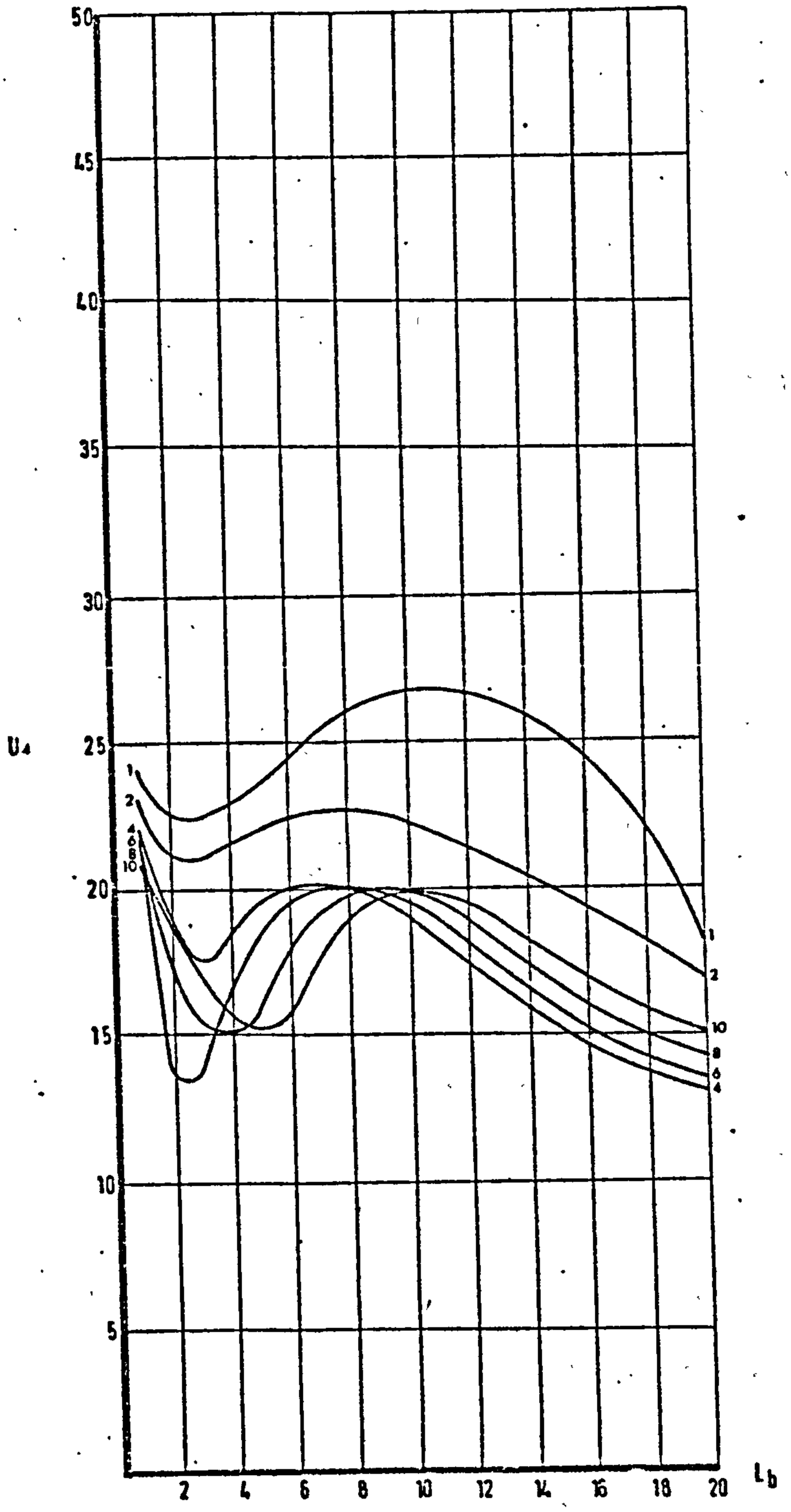


DIAGRAM 5.08: RELATIONSHIP BETWEEN NON-UNIFORMITY MEASURE U_4 AND BLOCK LENGTH FOR DIFFERENT SPACE SIZES

U_4 to a minimum at space 5 where it remains stationary with further increase in space size. For block lengths 2 - 3 the increase in spacing causes a gentle initial drop in U_4 values, then a rapid increase towards a minimum at space 6. This is followed by an increase in U_4 values with further increase in space size. This pattern continues with a decrease in range, until block length 10. An exception in this range is block length 5, where U_4 values decrease linearly with increase in space. For block lengths larger than 10, the behaviour of U_4 shown by block length 15 is common: U_4 falls sharply with increase in space to a minimum value at space 5, followed by a gentle increase on further increase in space size.

9.02 The relationship between U_4 and block length for different space sizes is shown in diagram 5.08. The behaviour of U_4 with change in block length and space size is such that the value of U_4, after an initial drop, increases with increase in block length until block length range 6 - 10 for different space sizes. Beyond that, it decreases with further increase in block length to reach minimum values towards block length 20. The highest U_4 values are shown at space size 1, whereas spacing 4 shows lowest values in the block length range 9 - 20. Space size 10 shows its lowest U_4 values at block length range 5 - 9 and space 6 has its lowest U_4 values in the 1 - 3 block.length range. As the diagram shows, there is a large interference in the values of U_4 despite the well-defined pattern of behaviour of the non-uniformity measure with change in the two form aspects. The initial drop in the value of U_4 as the block length increases (mainly in the block length range 2 - 5) varies with space size. With the smaller space sizes it is relatively a gentle drop and it becomes steeper for larger space sizes. The changes in U_4 with block length are less pronounced for larger spaces, whereas

the increase in space size from 1 to 2 shows remarkable differences in U_4 values for the range of block lengths.

COMPARISON BETWEEN THE DIFFERENT MEASURES OF NON-UNIFORMITY AS COMPUTED FROM POINT SPEED MEASUREMENTS

10.01 This family of non-uniformity measures shows wide differences in values and behaviour. Between some, the differences are simple and consistent throughout the range of forms considered, but in others the differences change with change in form aspects and range. The differences in behaviour are manifest in the sensitivity to change in form, positions of maxima and minima and the occurrence and extent of stationary values.

10.02 Diagrams 5.09 - 5.12 illustrate the differences by comparing the values and behaviour of U_1, U_2, U_3 and U_4 for block lengths 1, 3, 10 and 15 for different space sizes.

10.03 In diagram 5.09 it can be seen that U_4 has consistently the highest values of non-uniformity indices. In general, the largest discrepancy between U_4 and other values is shown at block length 1. The differences decrease with increase in block length. The lowest values are shown by non-uniformity measure U_2 while U_1 and U_3 lie in between in alternating positions with respect to U_2 and U_4, i.e., sometimes U_1 is higher than U_3 and sometimes it is the other way round. At block length 1 the non-uniformity measure U_4 decreases with increase in spacing to a minimum value at space 6, remaining stationary after that. This behaviour is shown also by U_2 and U_3. U_1 decreases initially to a minimum at space 5, but increases slightly with further increase in spacing.

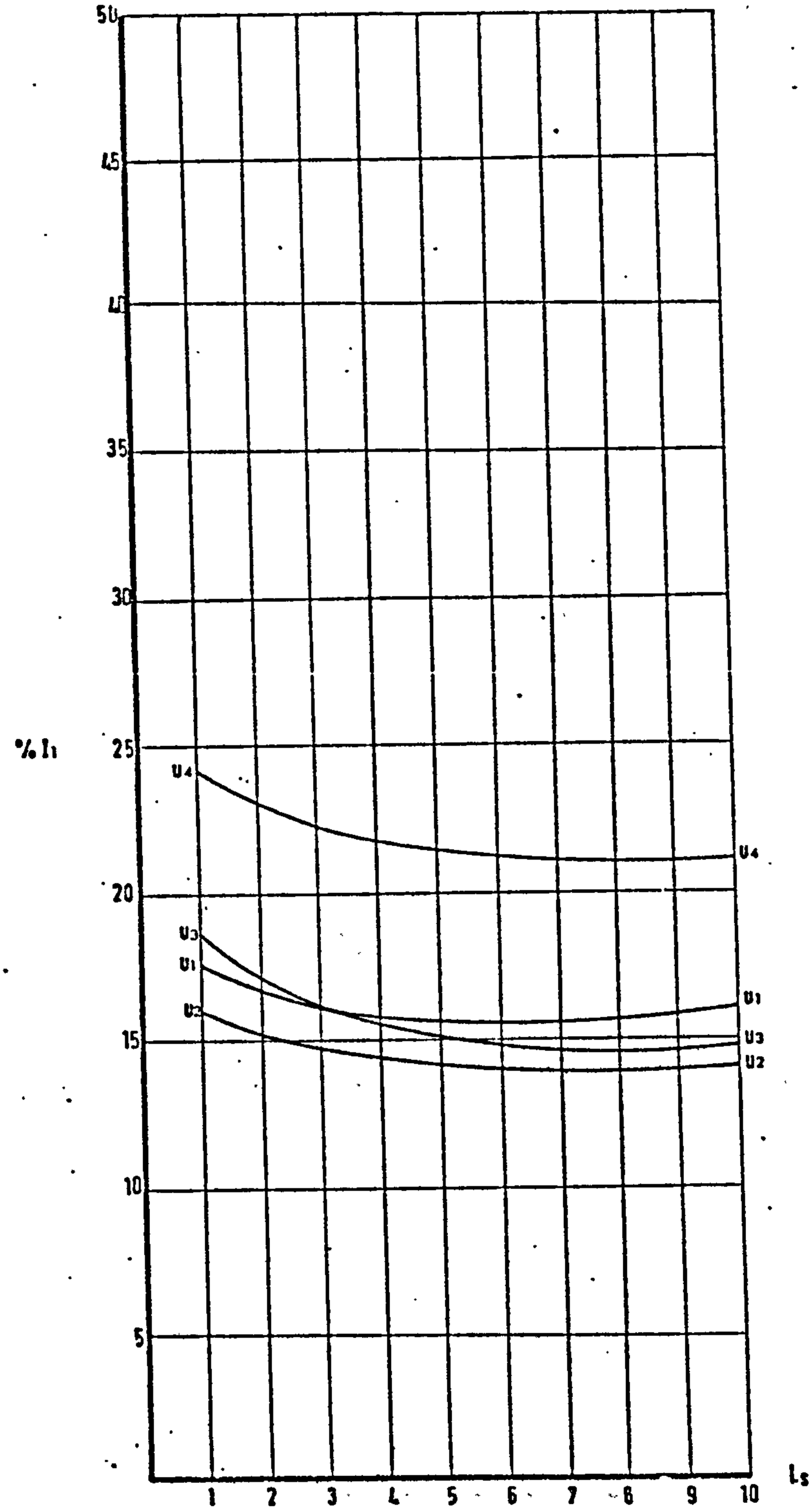


DIAGRAM 5.09: COMPARISON BETWEEN NON-UNIFORMITY MEASURES AT BLOCK LENGTH 1 FOR DIFFERENT SPACING SIZES

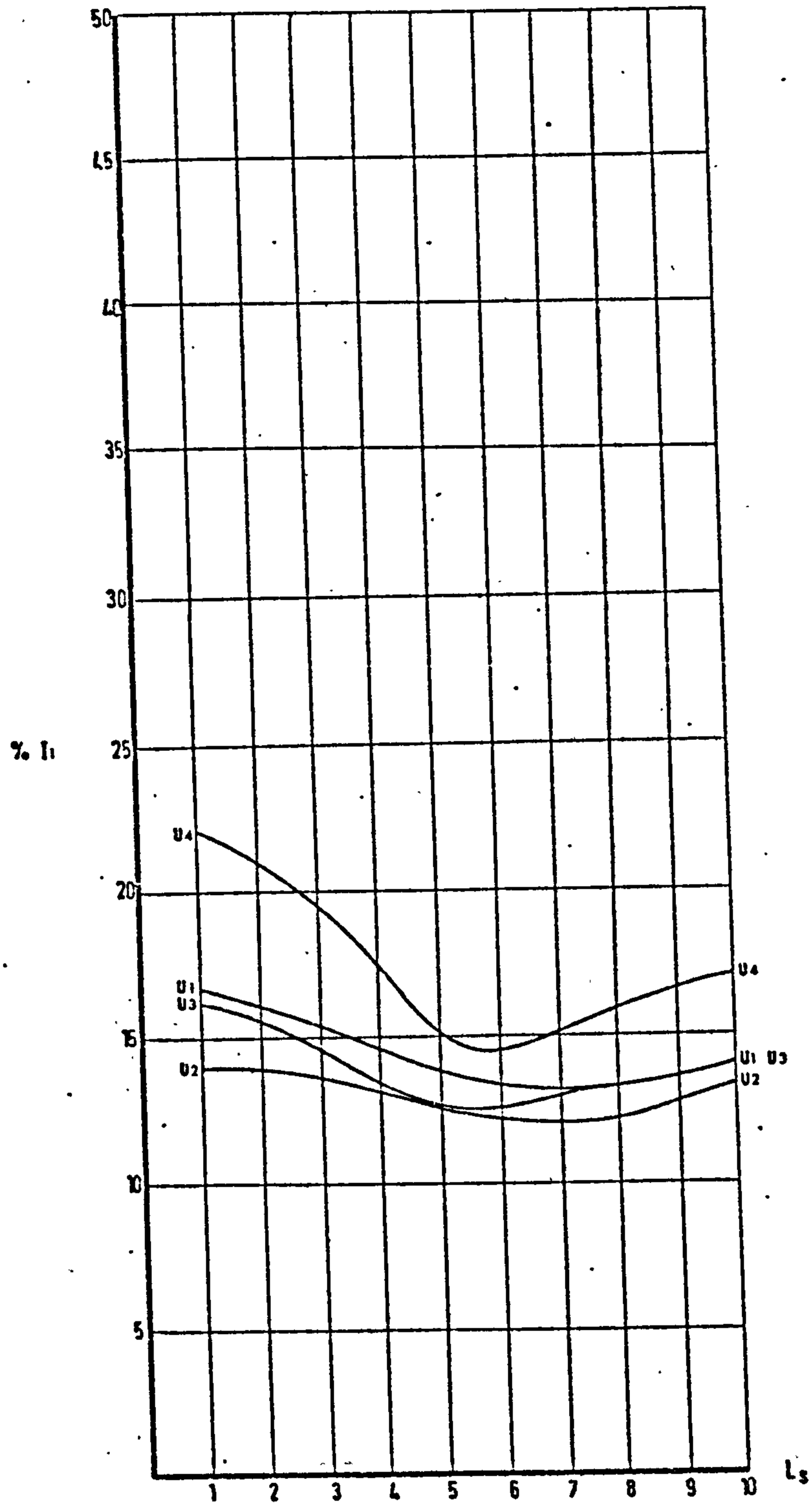


DIAGRAM 5.10: COMPARISON BETWEEN NON-UNIFORMITY MEASURES AT BLOCK LENGTH 3 FOR DIFFERENT SPACING SIZES

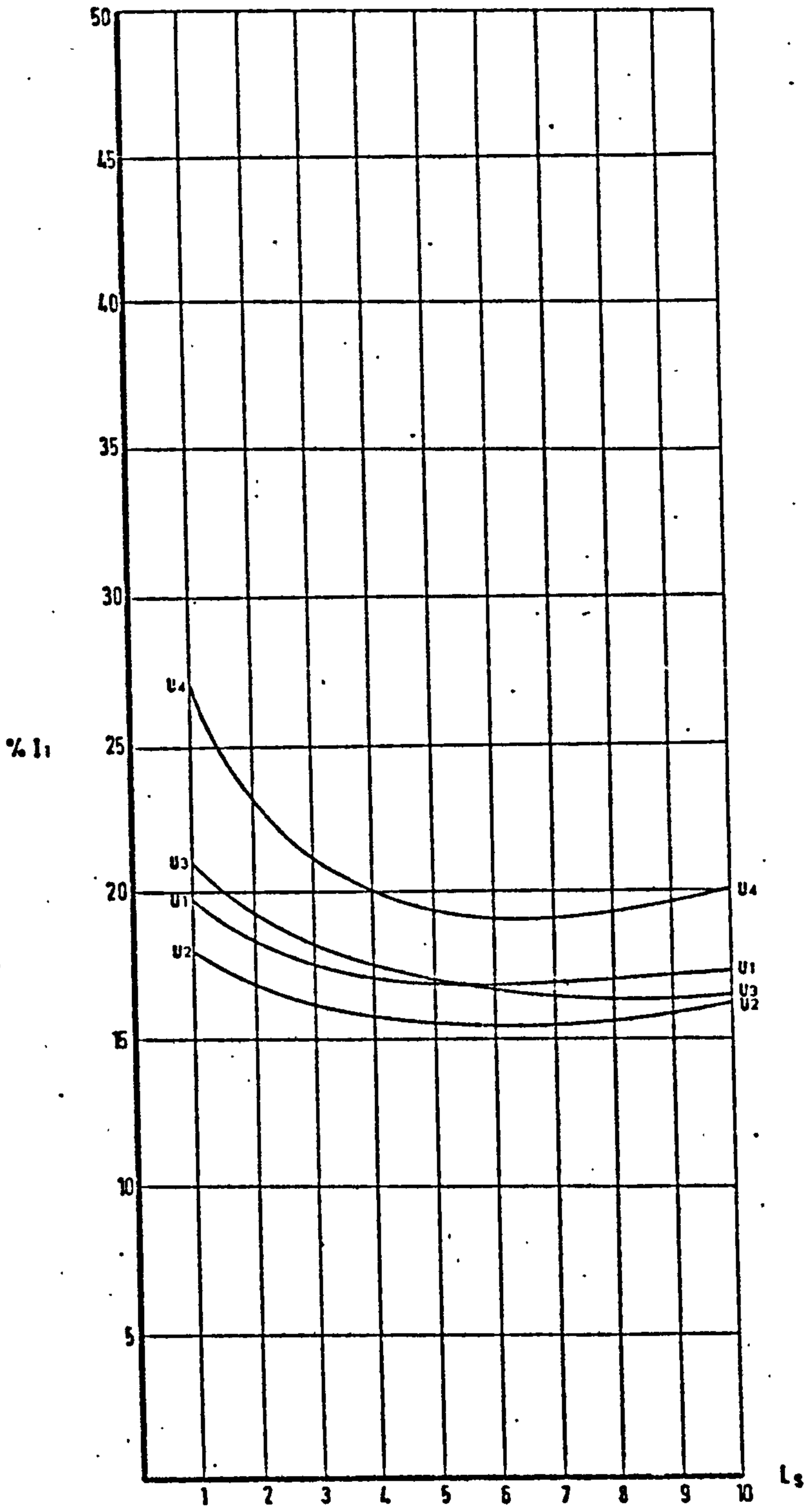


DIAGRAM 5.11: COMPARISON BETWEEN NON-UNIFORMITY MEASURES AT BLOCK LENGTH 10 FOR DIFFERENT SPACING SIZES

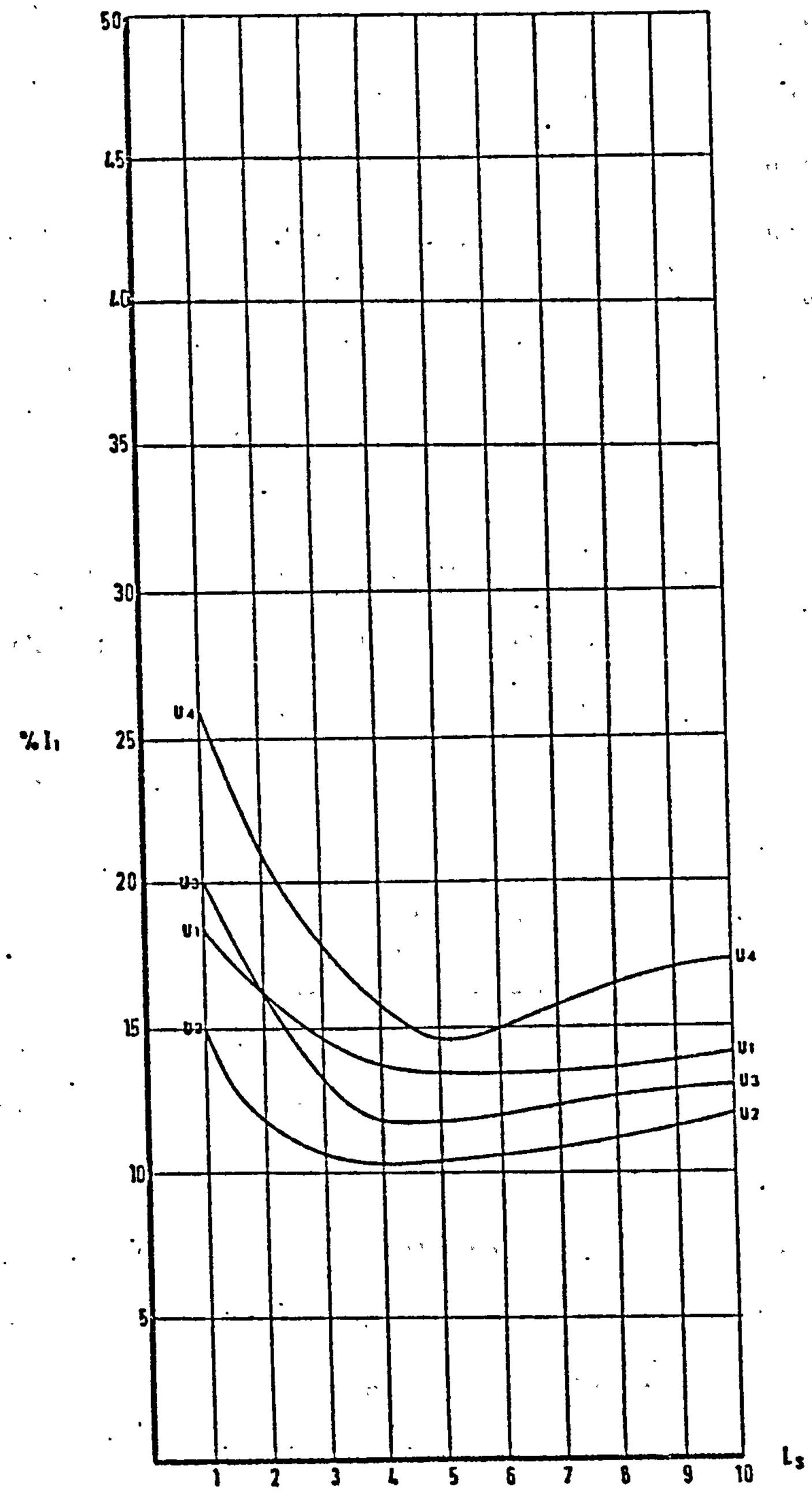


DIAGRAM 5.12: COMPARISON BETWEEN NON-UNIFORMITY MEASURES AT BLOCK LENGTH 15 FOR DIFFERENT SPACING SIZES

10.04 At block length 3, diagram 5.10, the pattern of change is more or less the same: decrease to a minimum value with increase in space size and an increase in the value of the non-uniformity index with further increase in spacing. There is, however, an appreciable difference in sensitivity or the rate at which the change occurs. This indicates that U_4 falls more rapidly than the others, which have less sensitivity to change in form and therefore show gentle slopes. The difference between U_4 and the other measures is largest at smaller space sizes and is lowest at space sizes 5 - 6.

10.05 The three non-uniformity measures, U_1, U_2 and U_3 show much closer values to each other than to U_4 at block length range 1 - 10. For larger block lengths the individual values shown by U_1, U_2, U_3 and U_4 are more widely spread.

POSSIBLE CAUSES OF THE DIFFERENCES BETWEEN U_1, U_2, U_3 AND U_4

11.01 It is clear from the formulations of U_1, U_2, U_3 and U_4 that their treatment of the data varies greatly. Measures based on the inter-quartile and percentile ranges are more likely to have a strong local bias, caused by the extent of the regions of lower and higher velocity values of the sample. By the nature of their formulation they tend to neglect the intermediate values and/or values in the highest or lowest brackets which may be crucial to the values of the non-uniformity index, specially in zones of relatively high range exposure values. This is clear from the comparison where arrangements of relatively uniform exposure (arrangements of relatively large block lengths and space sizes) show far less marked differences in non-uniformity indices computed by the four measures.

This problem is more likely to disappear in cases where the non-uniformity measure is of such formulation that it deals with the data in its totality whereby the intermediate values, usually overlooked in the geometric division of data of U_2 and U_3, will be individually included in the computations. These are significant considerations in arrangements where the intermediate values are of highest frequency and their exclusion in computations is likely to result in biased non-uniformity indices.

11.02 The two non-uniformity measures which consider the total sample in computing a non-uniformity index, U_1 and U_4, show a further discrepancy between themselves. U_4 usually has higher values. This is mainly due to the formulation of the measure, but it also varies with the distribution of the sample. In samples where the point exposure values have a wider range the difference between U_1 and U_4 values is relatively large; whereas in cases where the point exposure values are relatively close, the differences in U_1 and U_4 values are substantially lower. (This is shown at larger block lengths and space sizes.) Further, the range in non-uniformity index values for U_1 is generally smaller than that for U_4. This suggests that U_4 is a more sensitive measure to changes in form. This is a useful property when studying a linked progression of form aspects. Among the four non-uniformity measures, the sensitivity property is highest for the measure U_4.

COMPUTATIONS OF NON-UNIFORMITY INDICES FROM EXPERIMENTAL DATA USING DIFFERENT MEASURES OF NON-UNIFORMITY (AREA-BASED DATA)

12.01 In chapter III, a method based on interpolation was suggested to average direct point speed measurements over whole areas. This has proved useful in developing a quantitative visual impression of flow and

provided a good basis for the study and computation of a reliable exposure index. The same data structure will be used in this section to compute non-uniformity indices from measures of different formulation (section 4.00). The exposure index component of the different formulations will be I_5 which is computed from area-based data (chapter IV).

12.02 The new non-uniformity measures using area-based data structure are U_1', U_2', U_3' and U_4'. They have basically the same formulations as U_1, U_2, U_3 and U_4 respectively. The main difference between the two sets of measures is that the area for a given exposure value appears as a frequency element for that exposure value. Thus, U_1' is written as (section 5.00):

$$U_1' = \left[\left(\frac{\sum_{i=1}^{n} a_i(|V_i - I|)}{A}\right) / I\right] \times 100$$

and U_4' is stated as:

$$U_4' = \left[\left(\frac{\sum_{i=1}^{n} a_i\ (V_i - I)^2}{A}\right) / I\right] \times 100$$

U_2' and U_3' maintain the same formulation as U_2 and U_3 except that frequencies are represented by sizes of relevant area units rather than number of points.

13.00 Non-Uniformity Measure U_1':

13.01 Diagram 5.13 shows the relationship between U_1' and space size for different block lengths. The highest values of U_1' are shown by block length 1 and the lowest by block length 3. The pattern of change of U_1' with spacing varies with different block lengths. At block length 1 there is a constant and gentle drop of U_1' as the spacing increases. It reaches a minimum at space 7 and it remains at this minimum value until

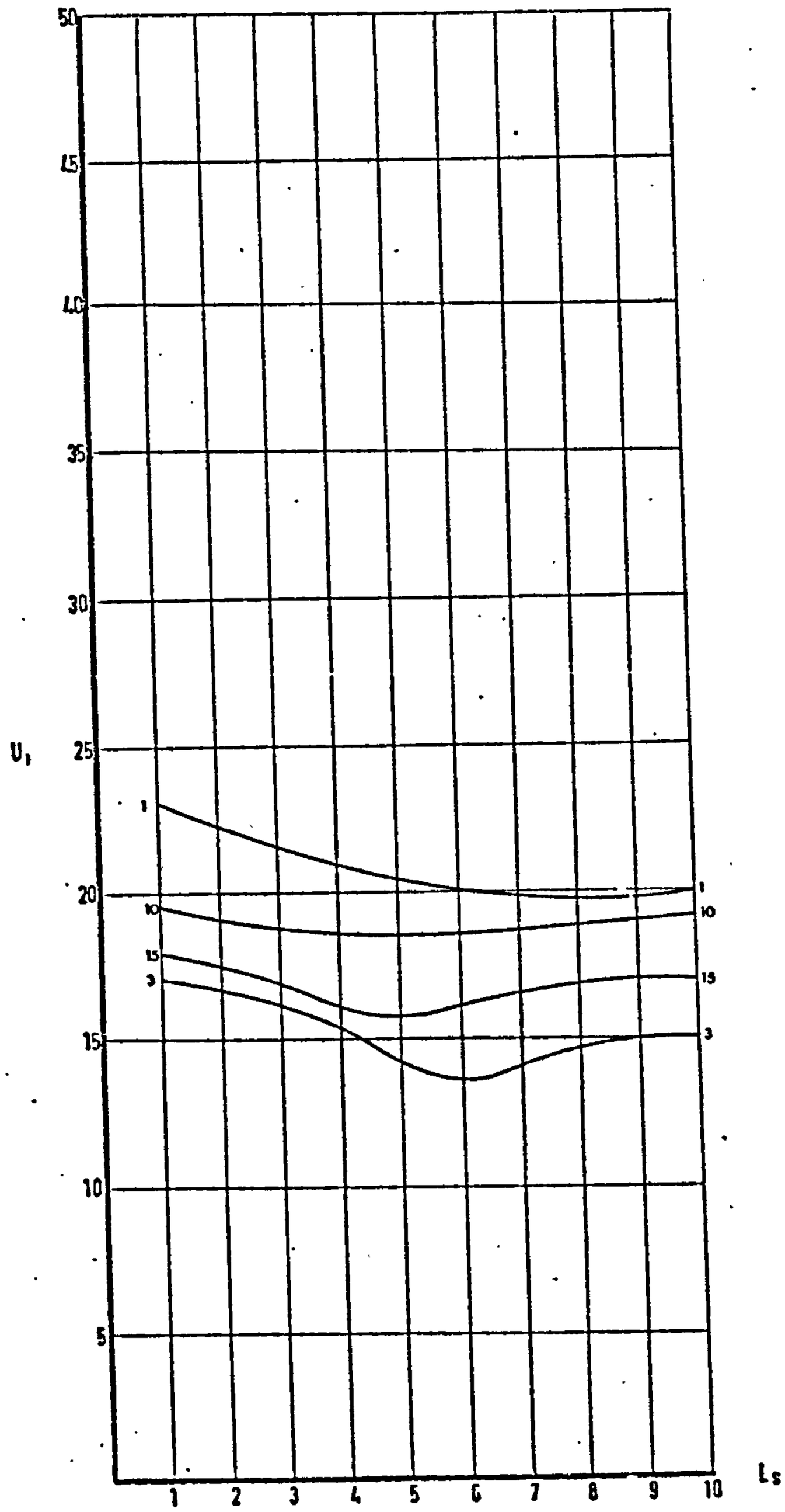


DIAGRAM 5.13: RELATIONSHIP BETWEEN NON-UNIFORMITY MEASURE U_1' AND SPACE SIZE FOR DIFFERENT BLOCK LENGTHS

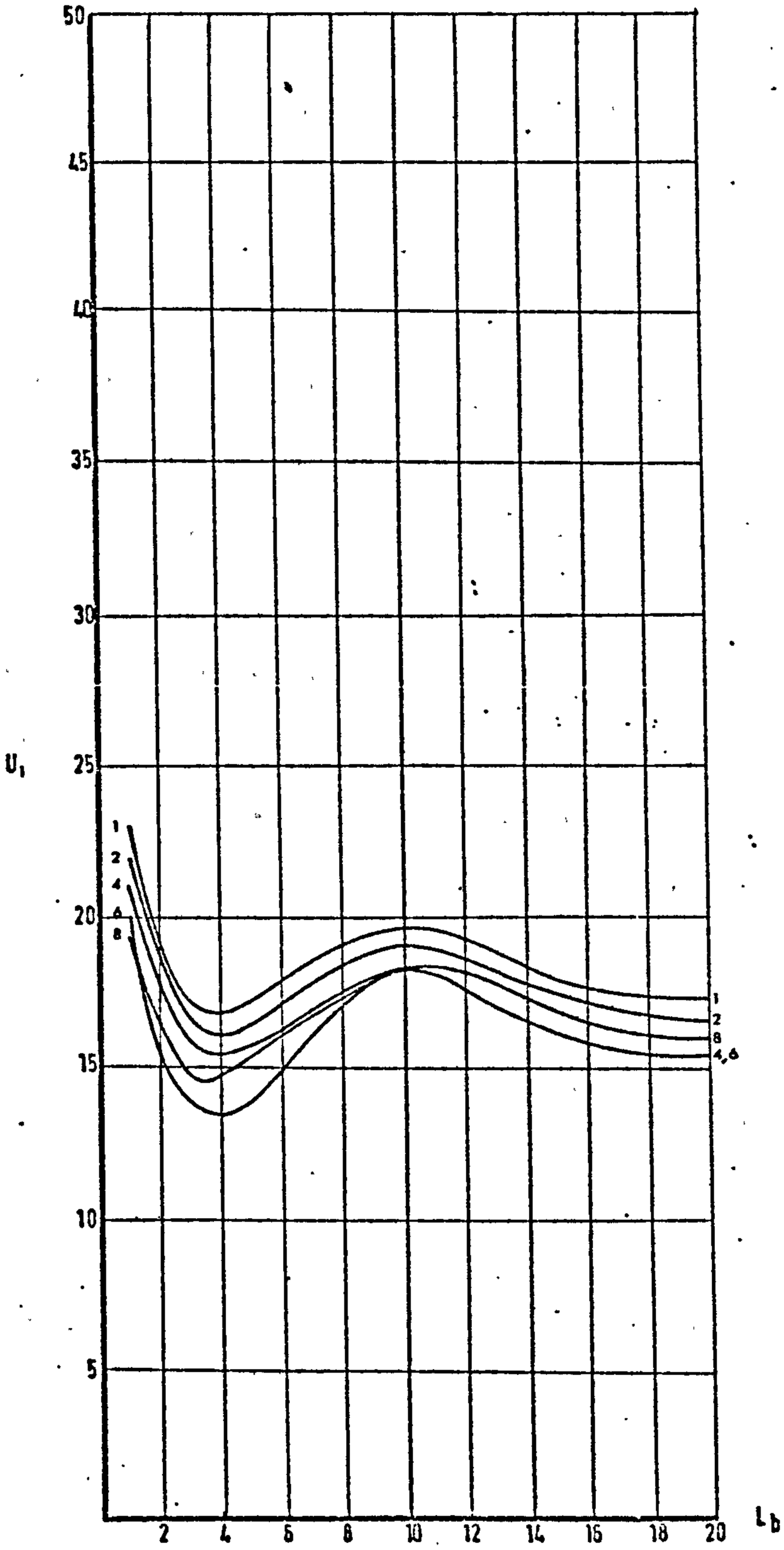


DIAGRAM 5.14: RELATIONSHIP BETWEEN NON-UNIFORMITY MEASURE U_1' AND BLOCK LENGTH FOR DIFFERENT SPACE SIZES

space 10. Block length 3 shows a small decrease in U_1' between spaces 1 - 4 but it falls rapidly beyond that to reach a minimum value at space 6. With further increase in space size the value of U_1' increases to 15% at space 8 and it remains unchanged for the rest of the space range. Block length 10 shows very little change in U_1' with increase in space. Block length 15 shows U_1' to decrease with increase in space to a minimum value at space 4, but it increases gently with further increase in spacing. For all block lengths, therefore, maximum U_1' values occur at smaller space sizes and minimum values, except for block length 1, occur at medium space sizes. The range between highest and lowest U_1' values in these arrangements is relatively lower than in U_1. The individual values of non-uniformity indices are higher for U_1' than in the case of U_1. In the case of U_1 the highest values are shown by block 10, whereas with U_1' they are shown by block length 1. The lowest values of U_1' occur for block length 3, but those of U_1 occur mostly for block length 15.

13.02 The relationship between U_1' and block length for different spacings is shown in diagram 5.14. This shows that the highest values of U_1' are taken by space 1 and the lowest values by space 6. The behaviour of U_1' with respect to change in block length for different spacings is such that it takes maximum values at block length 3 and it increases towards block length 10 before it decreases again. The values of U_1' for different spacings are very close together, showing a small range within sets of space sizes. The different space sizes tend to reach stationary values around block length 16. The general pattern of behaviour of U_1' with block length for different space sizes shows substantial differences when compared with U_1. These concern the range and the positions of maximum and/or minimum values. For U_1 the maximum values usually occur around block length 10 and the minimum values, except for block length

1, occur around space size 18.

14.00 Non-Uniformity Measure U_2':

14.01 Diagram 5.15 shows the relationship between U_2' and space size for different block lengths. The values given by this non-uniformity measure are generally lower than U_1'. The highest values are shown by block length 1 and the lowest values by block length 3. For all block lengths, the positions of the maximum values are at space size 1. The positions of the minimum values differ. For block lengths 1, 10 and 15, the minima occur at space size 5, whereas space 7 is the position of minimum values for block length 3. The behaviour of U_2' with change in block length differs according to the space size. With block length 1 there is a constant and slow fall in U_2' with increase in space until space 5 and it remains stationary until space 10. Increasing the space size for block length 3 causes U_2' to fall, first slowly and then repidly to reach a minimum at space size 7. On further increase of spacing U_2' increases slightly towards space 10. Block length 10 shows relatively small changes in U_2' with increase in spacing, but it has a definite minimum value in the space range 4 - 7. Block length 15 shows the same behaviour of U_2' as block length 3 except that the minimum value occurs earlier, at space size 5.

14.02 Comparison between U_2 and U_2' for the same block lengths and spacing ranges shows differences in the occurrence of highest and lowest values as well as in the pattern of change of the non-uniformity values with increase in spacing. U_2 has highest values at block length 10 and lowest values at block length 15. The change in U_2 with increase in spacing for block length 15 shows a steep drop between spacing 1 and 3 whereas the values of U_2' changes slowly in the same range. At block

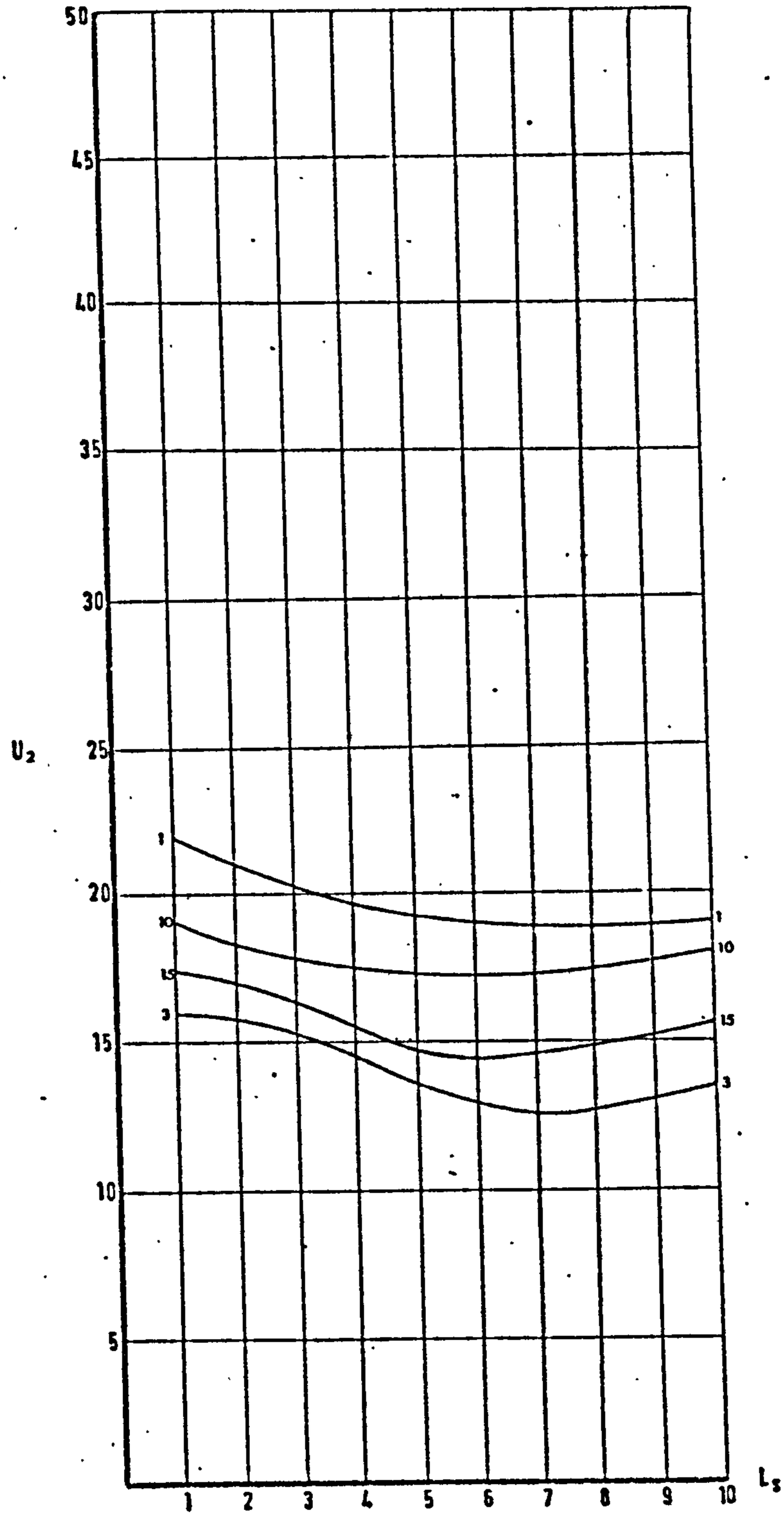


DIAGRAM 5.15: RELATIONSHIP BETWEEN NON-UNIFORMITY MEASURE U_2' AND SPACE SIZE FOR DIFFERENT BLOCK LENGTHS

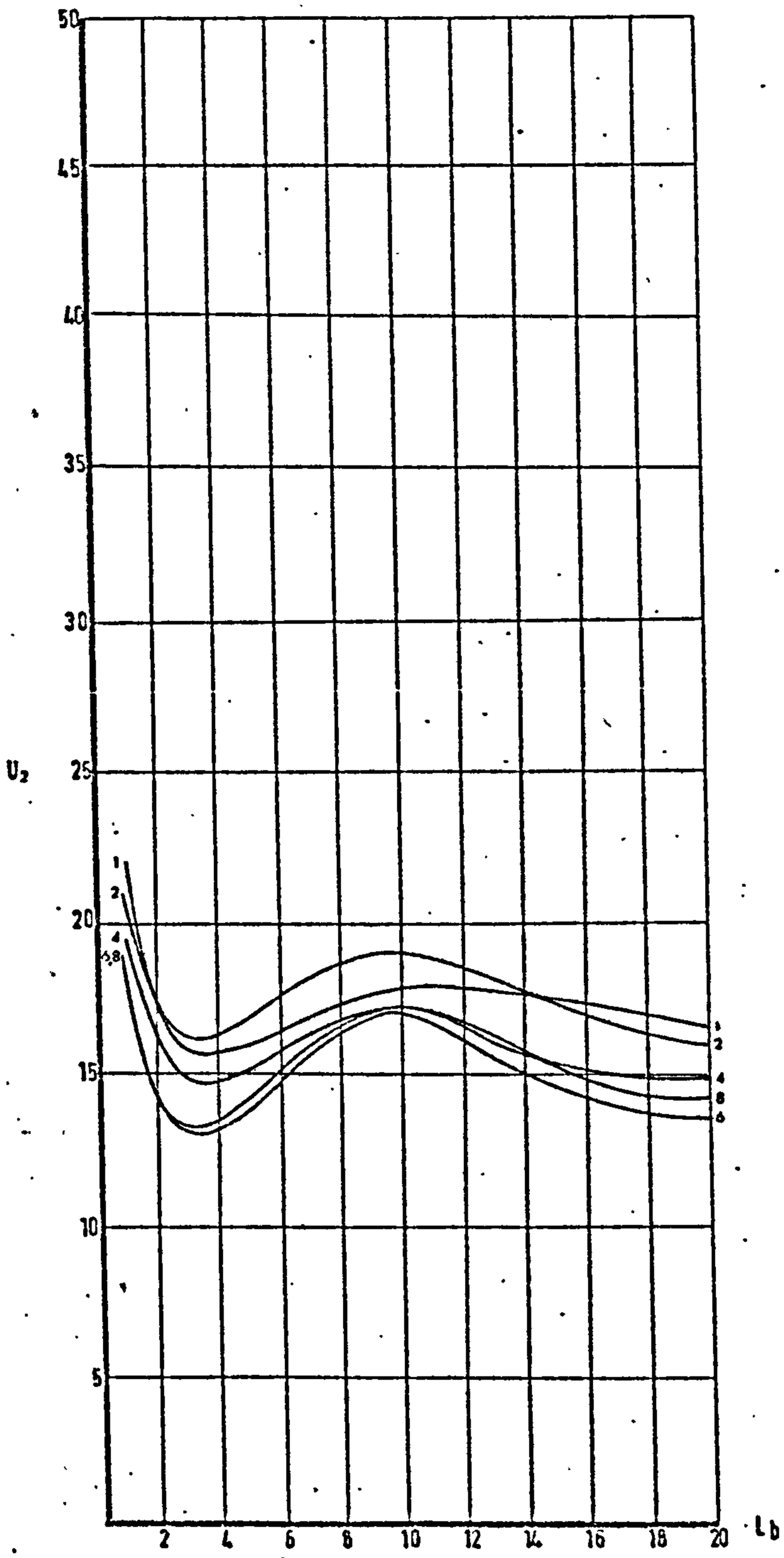


DIAGRAM 5.16: RELATIONSHIP BETWEEN NON-UNIFORMITY MEASURE U_2' AND BLOCK LENGTH FOR DIFFERENT SPACE SIZES

length 1 the change in U_2 is relatively small compared to that of U_2' for the same block length. The two measures, however, agree on the position of maximum values (which occur at space 1) but differ in the positions of minimum values.

14.03 The relationship between U_2' and block length for different space sizes is shown in diagram 5.16. The behaviour of U_2' with respect to block length is such that maximum values occur at block length 1, falling steeply as the block length increases to 3. Between block lengths 3 - 10 there is an increase in U_2' values and beyond this range U_2' values begin to fall. The minimum values of U_2' for different space sizes occur around block length 3. Spacings 4, 6 and 8 have almost coincidental values at block length 10. The interference in values between the different space sizes is substantial and the values of U_2' are closer than in the case of U_2. U_2 and U_2' show large differences in range, with U_2 having a wider range of values, especially at larger block lengths. For space sizes 1 and 2, the values of U_2' are almost coincidental for the larger block lengths, but they diverge widely for U_2 at the same block length range. The maximum values of U_2 occur at block length 10, whereas these values occur at block length 1 in the case of U_2'. The position of the minimum values also differ. The minimum values in the case of U_2' occur around block length 3, but in the case of U_2 they occur around block length 18. U_2', however, shows similarity in the positions of maximum and minimum values with U_1'. It also shows similarities in the range of values with that of U_1'. The main difference between U_1' and U_2' is that the values yielded by U_1' are slightly higher than those of U_2'.

15.00 Non-Uniformity Measure U_3':

15.01 The third non-uniformity measure, U_3', and its relationship to space

size is shown in diagram 5.17 for different block lengths. It shows generally higher values than U_1', U_2' and U_3. As in U_1' and U_2' the highest values of U_3' occur for block size 1 and the lowest values show at block length 3. This is different from what happens in U_3 where the lowest values occur either around block length 10 or 15. The range of values of U_3' is larger than that of U_3. The change in U_3' values is relatively gentle. The positions of minimum values depends on block length. For block length 1 this occurs at space 6 with a slight increase towards space 10. This behaviour differs from the previous cases where the value of the non-uniformity index remains stationary at the minimum value beyond space 6 for block length 1. Another deviation from U_1' and U_2' is seen at block length 10 where the minimum value occurs at space 6 and remains unchanged with increase in space. With U_1' and U_2' an increase in value occurs after the minimum value is reached.

15.02 Diagram 5.18 shows the relationship between U_3' and block length for the range of space sizes. The maximum values occur at block length 1 with a steep drop as the block length increases to 3. Further increase in block length increases the value of U_3' until block length 10, beyond which U_3' falls in value. The minimum values occur around block length 19 - 20 with some space sizes showing another minimum around block length 3. The range of values of U_3' is relatively small with space sizes 6 - 8 having very close U_3' values.

15.03 Comparing U_3' and U_3 shows that there are wide differences in the values and behaviour of the non-uniformity index in relation to spacing and block length. The main differences concern the positions of maximum and minimum. For space size 1 the maximum value of U_3, diagram 5.06, occurs towards the larger block lengths, whereas the highest values of U_3'

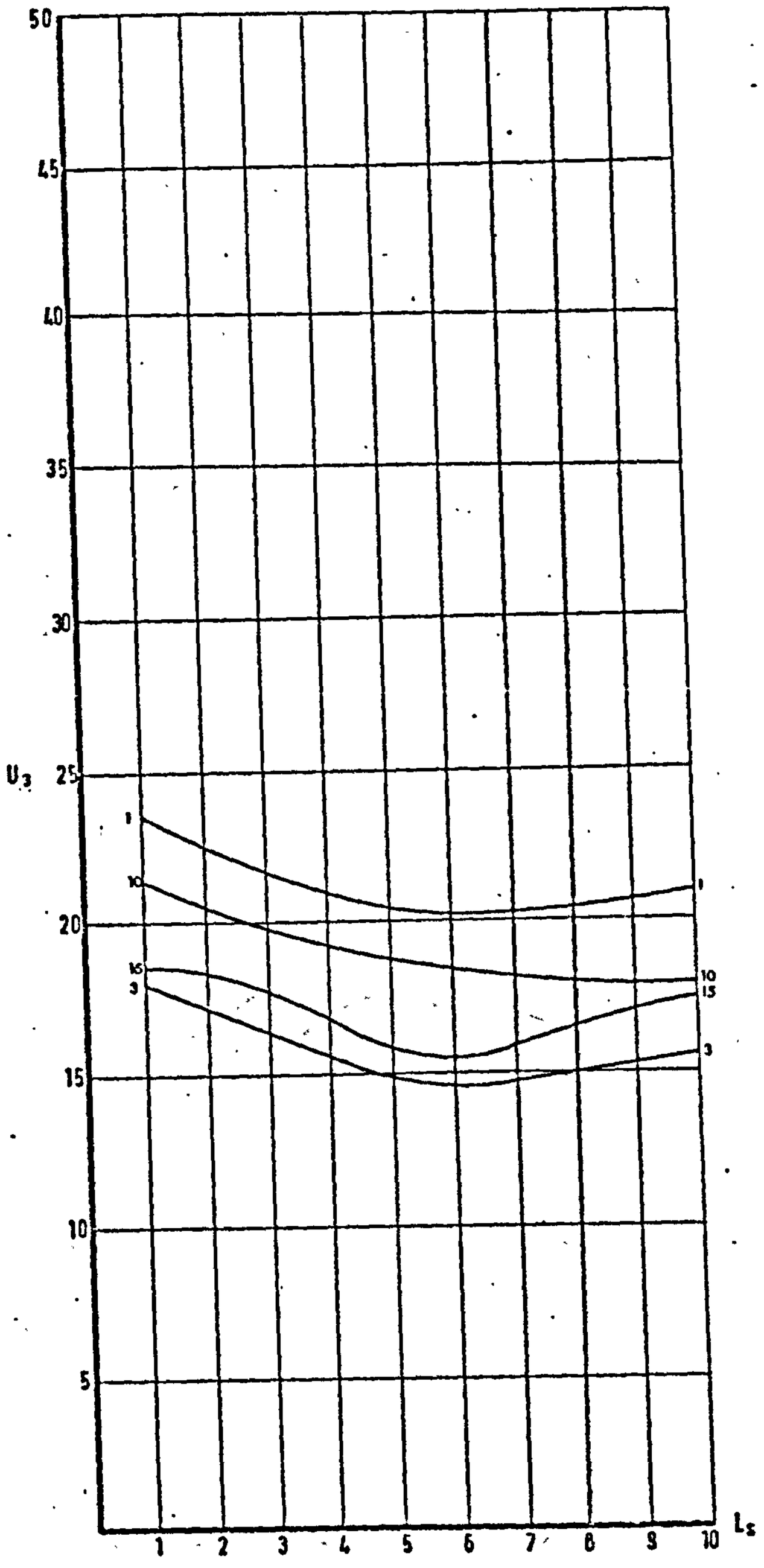


DIAGRAM 5.17: RELATIONSHIP BETWEEN NON-UNIFORMITY MEASURE U_3' AND SPACE SIZE FOR DIFFERENT BLOCK LENGTHS

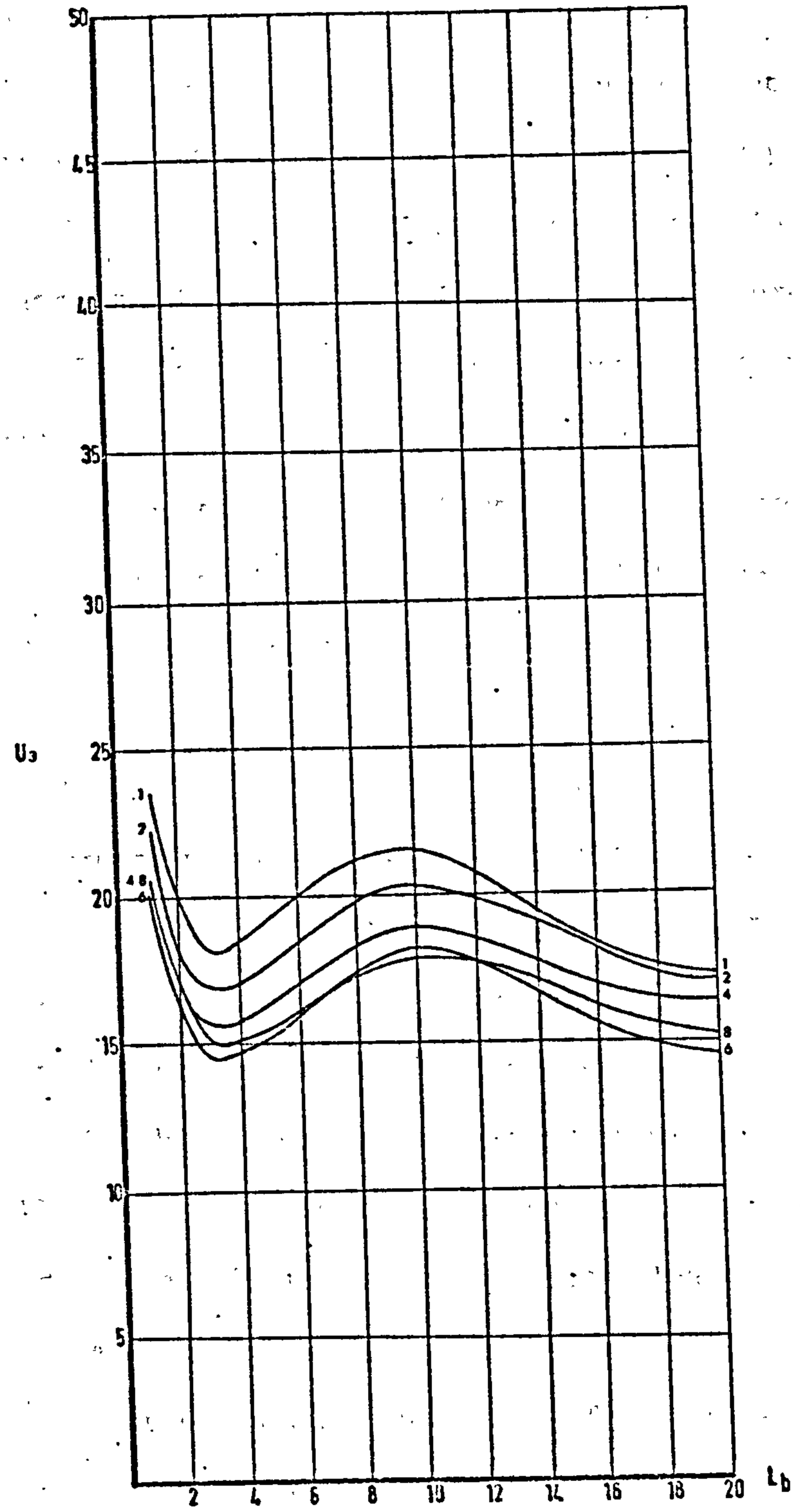


DIAGRAM 5.18: RELATIONSHIP BETWEEN NON-UNIFORMITY MEASURE U_3 AND BLOCK LENGTH FOR DIFFERENT SPACE SIZES

occur at block length 1. The minimum values for the same spacing are shown to occur at block length 20 by U_3' and at block length 6 by U_3. At space size 2 the maximum value of U_3' occurs at block length 1, whereas U_3 shows two positions of maxima: at block length 1 and at block length range 13 - 20. For space sizes 4 - 6 the value of U_3 falls slowly with increase in block length. They reach their minimum values around block length 12 and remain stationary until block length 20. This is different from the behaviour of U_3' for the same space sizes. Further, at space 8, U_3 falls slowly to minimum at block length 10 and it increases slightly as the block length increases to 20. U_3' behaves differently and it falls rapidly between block lengths 1 - 3. Between block lengths 3 - 10 it increases and it falls again beyond this range.

16.00 Non-Uniformity Meausre U_4':

16.01 The non-uniformity measure U_4' shows a very different behaviour pattern from the previous measures. Its relationship to space size is shown in diagram 5.19 for different block lengths. The maximum values occur at space size 1, but the minimum values positions vary with different block lengths. For block length 1, the minimum value of U_4' occurs in the space range 8 - 10. For block length 2 it occurs in the space range 6 - 10. The positions of the minimum values for block lengths 3 - 5 are not as extensive in space size range and they occur around space size 6. Block length 10 shows an extensive space range of minimum value of the non-uniformity measure: space range 4 - 8. This range of minimum values is sharply decreased for longer block lengths. At block length 15 the minimum value of U_4' occurs at spaces 4 - 5. The change in U_4' with increase in spacing is relatively gentle for block lengths 1 - 2. For block lengths 3 - 5 the value of U_4' falls slowly at the beginning, but sharply as it takes towards its minimum value around space 6. On

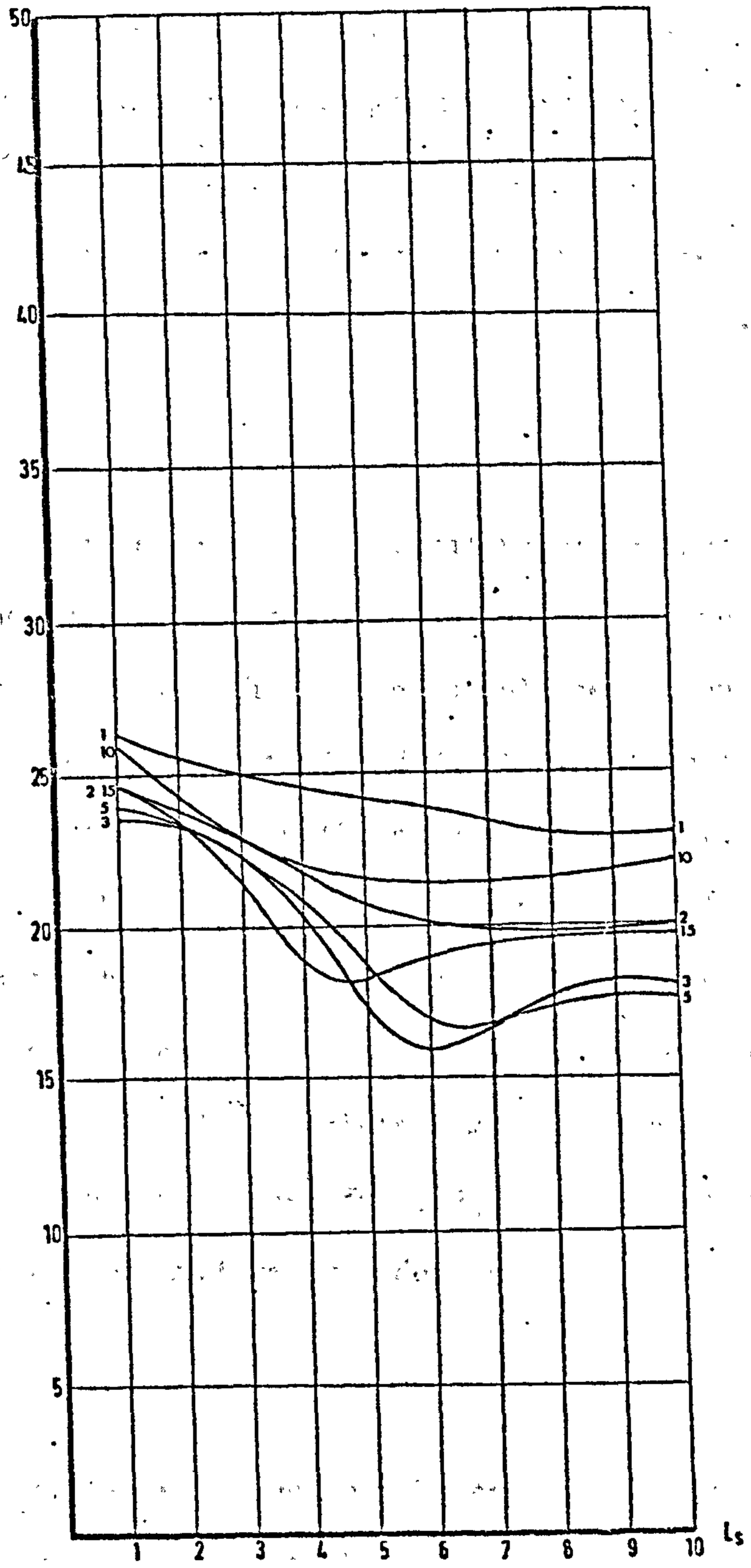


DIAGRAM 5.19: RELATIONSHIP BETWEEN NON-UNIFORMITY MEASURE U_4 AND SPACE SIZES FOR DIFFERENT BLOCK LENGTHS

further increase in spacing, U_4' increases slowly and remains stationary at the same value for space range 8 - 10. This pattern is shown later at block length 15, except that the stationary values have a wider space range. Block length 10 shows less marked changed in U_4' values, especially in the space range 5 - 10. U_4' shows generally higher values of non-uniformity indices than all previous non-uniformity measures. (There is, however, one exception, that is the values of U_4 at space 1 with block length 10 and 15.)

16.02 Apart from the differences in individual values of non-uniformity indices U_4' and U_4 show close patterns of behaviour as the space size changes for different block lengths. One notable deviation from this is the difference in the behaviours of U_4' and U_4 at block length 5. In this case, U_4 decreases almost linearly with increase in spacing, whereas U_4' falls initially slowly, then rapidly to reach a minimum value before it increases again with further increase in spacing. The behaviour of U_4' at block length 5 is more consistent with those immediately preceding and/or following it. It is also consistent with the behaviour of U_4 for the same set of block lengths. Therefore, U_4 is likely to give a more representative behaviour of uniformity index at block length 5 with change in space size.

16.03 The relationship between U_4' and block length for different space sizes is shown in diagram 5.20. It shows that U_4' generally has maximum values at block length 1 and that there is more than one position of minimum values for some space sizes. The positions of minimum values are around block length 4 and/or block length 20. Between block lengths 1 and 4 there is a drop in the values of U_4'. This drop is steep for larger space sizes and relatively gentle for smaller spaces. The values of U_4'

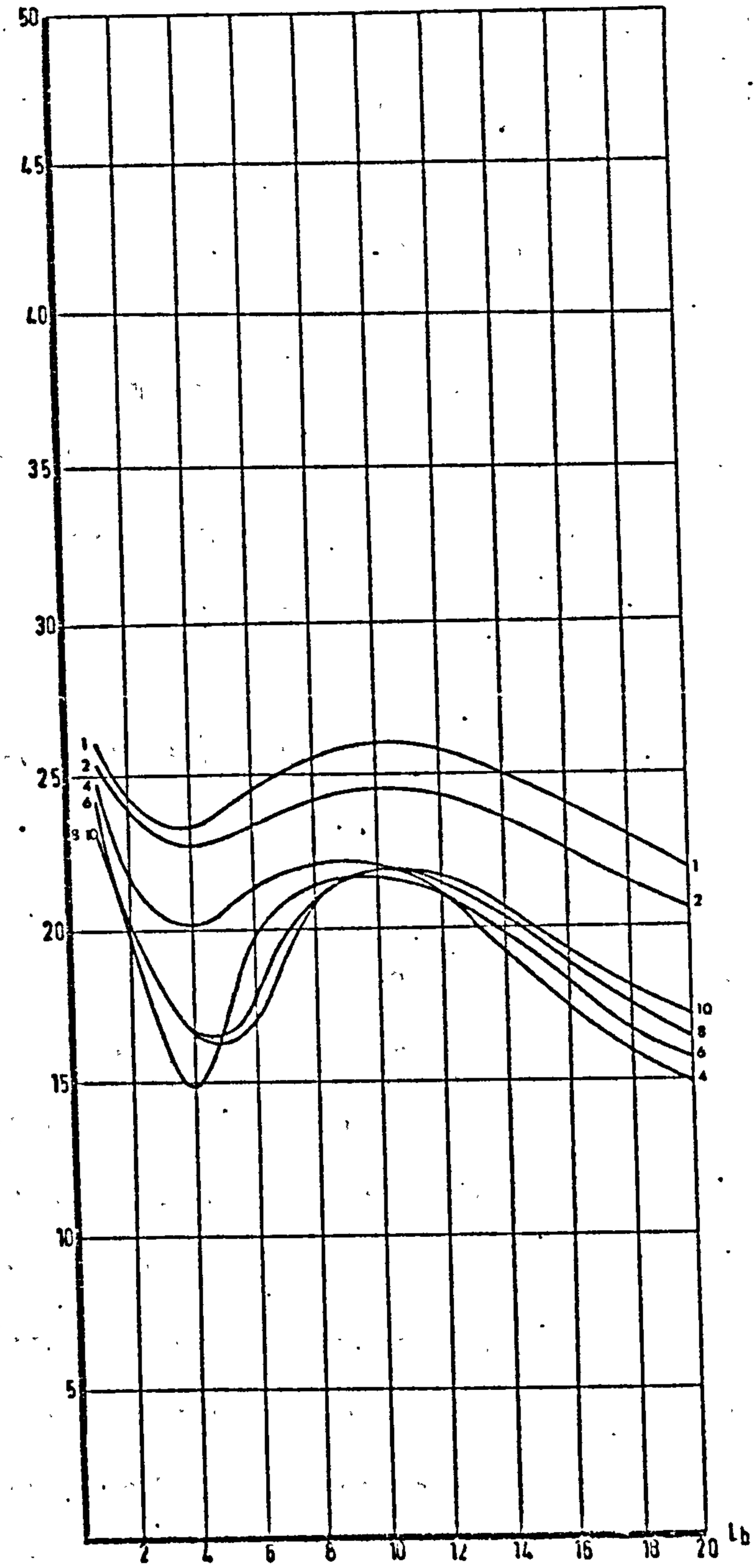


DIAGRAM 5.20: RELATIONSHIP BETWEEN NON-UNIFORMITY MEASURE U_4 AND BLOCK LENGTH FOR DIFFERENT SPACING SIZES

for space size 4 are higher than those for spaces 6 - 10, but they take a sharp turn after that and become lower for larger block lengths. Similarly, the U_4' values for spaces 6, 8 and 10 alternate positions of higher and lower values in relation to each other as the block length increases, diagram 5.19. This behaviour is also shown by U_4 but the values of U_4' for the different space sizes are much closer than those of U_4 for the same space sizes. Comparing the fall in values of U_4' and U_4 between spaces 1 and 2, diagram 5.20, U_4 shows a much larger drop than U_4', especially for block lengths in the range 8 - 18. For spacing 1, the maximum value of U_4 occurs at block length 10, whereas U_4' shows two positions of maximum values: at block lengths 1 and 10.

COMPARISON BETWEEN THE DIFFERENT MEASURES OF NON-UNIFORMITY AS COMPUTED FROM AREA-BASED DATA STRUCTURE

17.01 The different measures of non-uniformity U_1', U_2', U_3' and U_4' which are computed from an area-based data structure vary in their values of non-uniformity indices for the different arrangements. These differences are illustrated by the comparison of different measures of non-uniformity for a range of block lengths, diagrams 5.21 - 5.24. In diagram 5.21 the relationships of the four measures to space size are shown for block length 1. All four measures show the same position of maximum non-uniformity index values. Except for U_3', they show a decrease with increase in spacing until a minimum value is reached around space 6 and they remain stationary at this value until space 10. U_3, however, after reaching a minimum value continues to increase with the increase of spacing. For any one measure the range of non-uniformity index values is relatively small and the change in values is slow. U_4' gives the highest values and U_2' gives the lowest values. U_1' and U_3' give values between those of U_2' and U_4'

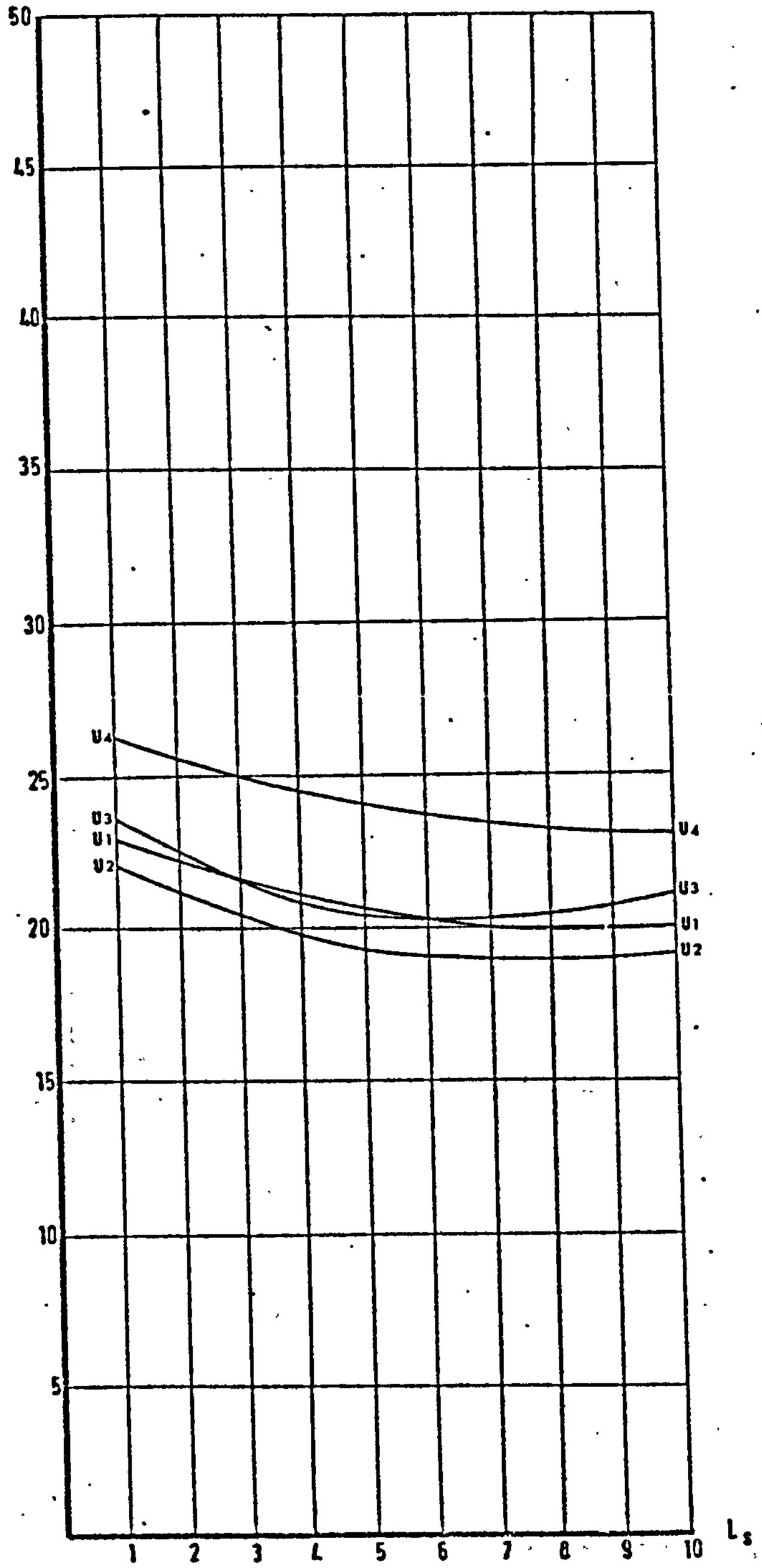


DIAGRAM 5.21: COMPARISON BETWEEN NON-UNIFORMITY MEASURES AT BLOCK LENGTH 1 FOR DIFFERENT SPACE SIZES

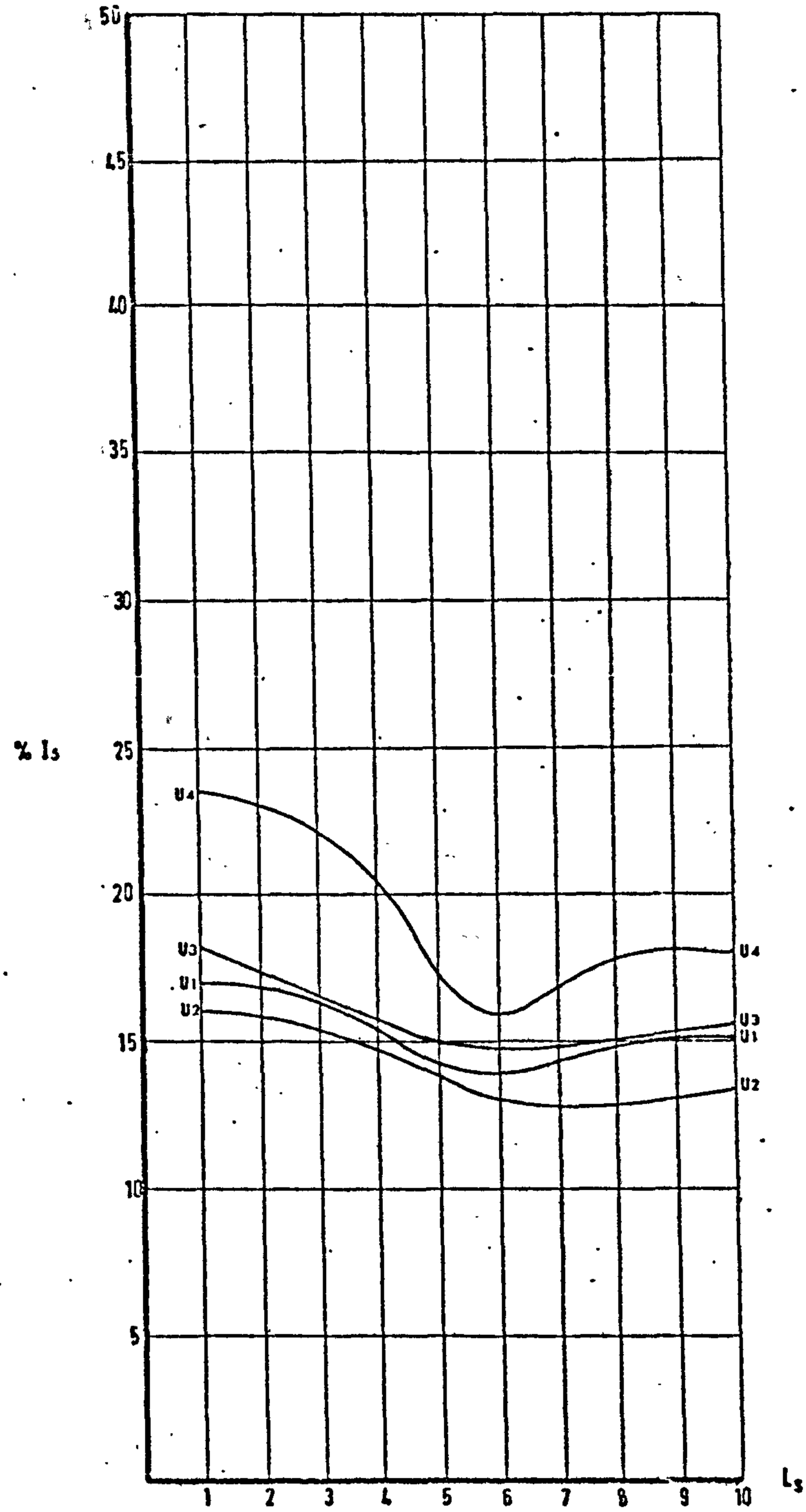


DIAGRAM 5.22: COMPARISON BETWEEN NON-UNIFORMITY MEASURES AT BLOCK LENGTH 3 FOR DIFFERENT SPACE SIZES

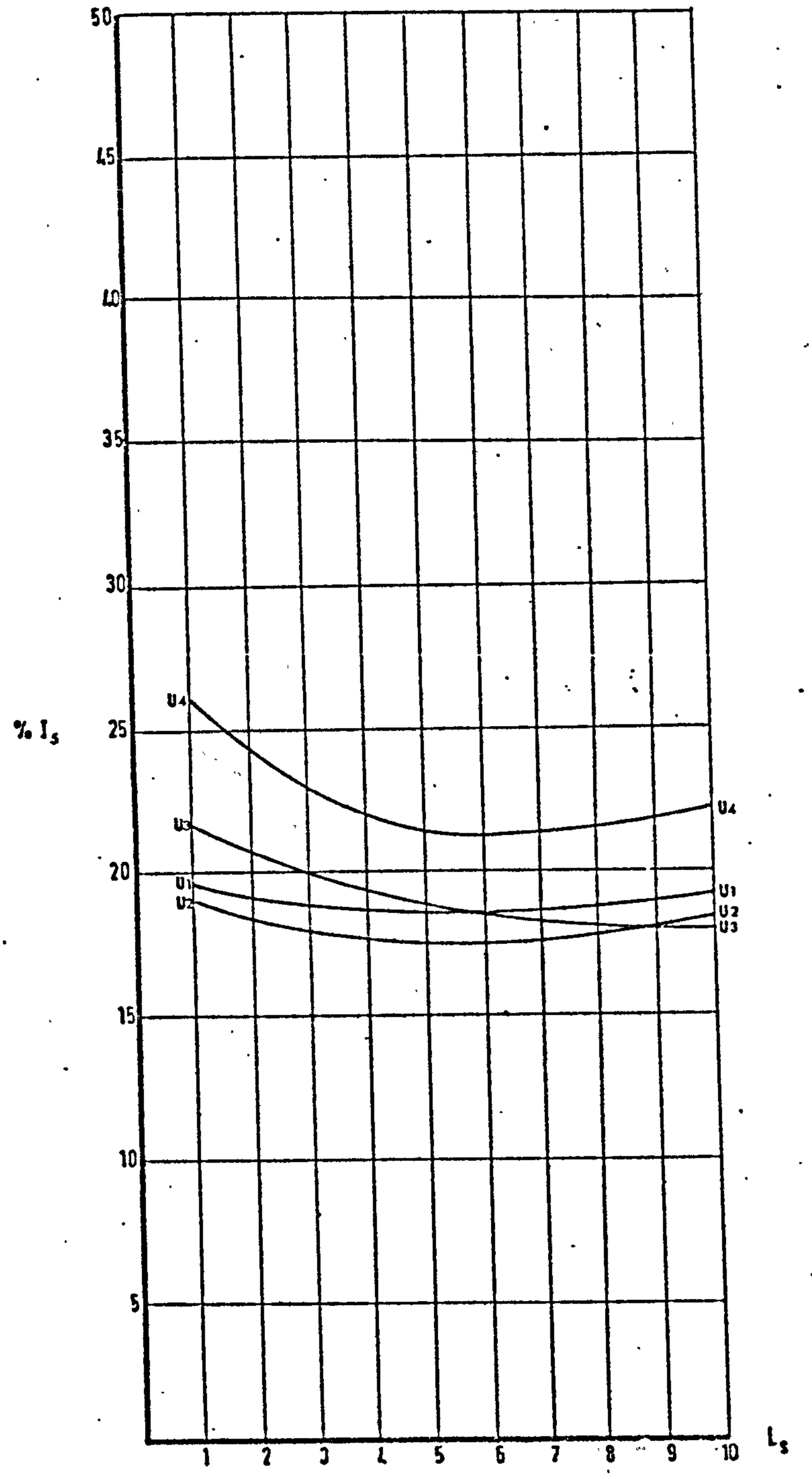


DIAGRAM 5.23: COMPARISON BETWEEN NON-UNIFORMITY MEASURES AT BLOCK LENGTH 10 FOR DIFFERENT SPACE SIZES

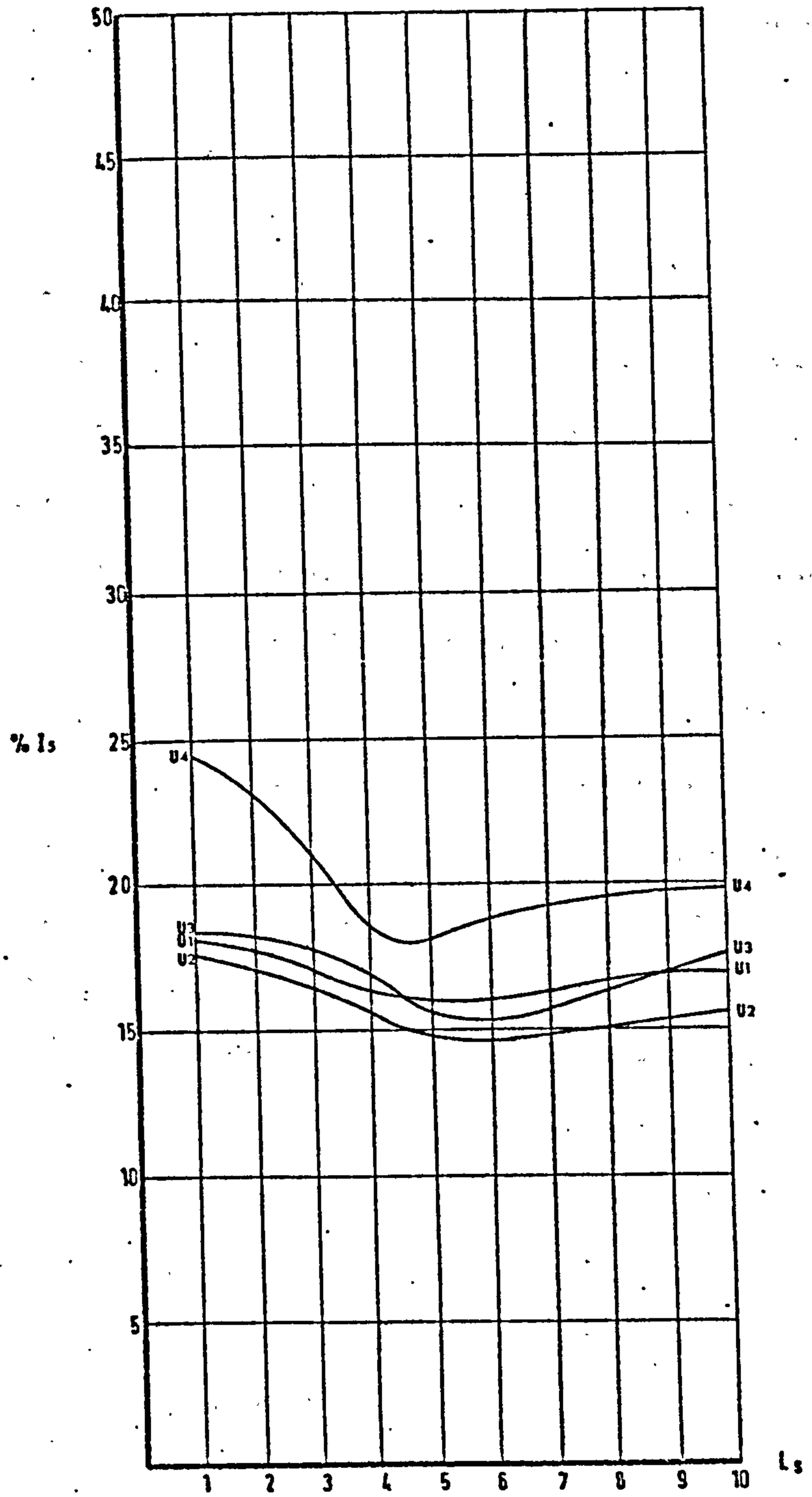


DIAGRAM 5.24: COMPARISON BETWEEN NON-UNIFORMITY MEASURES AT BLOCK LENGTH 15 FOR DIFFERENT SPACE SIZES

but much closer to those of U_2'. The non-uniformity indices shown by U_3' and U_1' are very close and they coincide for most of the space range. The range of non-uniformity index values shows a smaller discrepancy than the values shown by the measures U_1, U_2, U_3 and U_4 for the same block length.

17.02 At block length 3, diagram 5.23, the non-uniformity index values and the behaviour of the measures in relation to space size show wider disparities. Generally, U_4' shows higher values than U_1', U_2' or U_3' and U_2' giving the lowest values. U_1' and U_3' show closer values to each other and are relatively slightly higher than U_2'. The differences in index values between U_4' and those of the other measures are greatest at shorter space sizes and they decrease to a minimum discrepancy at intermediate space sizes. U_4' decreases first slowly and then rapidly towards its minimum value at space 6. Beyond space 6 it increases relatively slowly towards space 10. This pattern of behaviour is different from that of U_1', U_2' and U_3'. These decrease very slowly to their minimum values around space 6. For U_3' this decrease is almost linear. The increases in index values beyond space 6 are very small compared with that of U_4' and U_2' can be regarded as having stationary values beyond space 6. As in the case of block length 1 the range of the non-uniformity index values shown by U_1', U_2', U_3' and U_4' is smaller than that shown by U_1, U_2, U_3 and U_4 for the same block length and space sizes.

17.03 Diagram 5.23 shows a comparison between non-uniformity index values at block length 10 for different space sizes. The highest values are shown by U_4' but the lowest values are taken partly by U_2', at the smaller and intermediate sizes, and by U_3' at the larger space sizes. The difference between U_4' and the values of the other measures are smaller for

this block length than for the previous cases. The highest non-uniformity index values occur at smaller space sizes and they decrease gradually with increase in space size. Except for U_3' which continues to decrease until it reaches a stationary minimum value at space 8, all measures reach a minimum value around space 5 and show a slight increase with further increase in spacing.

17.04 Larger block lengths show a pattern of change in non-uniformity indices almost similar to that of block length 3. This is shown in diagram 5.24 for block length 15. The values of the non-uniformity indices are slightly higher than those for block length 3. The highest index values are shown by U_4' and the lowest values are given by U_2'. U_1' and U_3' interchange positions between U_4' and U_2' values. For smaller space sizes U_3' is higher than U_1', but lower for larger space sizes. U_4' decreases relatively sharply between spaces 1 and 4 where it reaches its minimum value. Beyond space 4, U_4' increases gently with further increase in space. The other measures U_1', U_2' and U_3' show a more gentle change, decreasing towards minimum values around space 6 and increasing slightly with further increase in space size. This block length is the only case where the behaviour of the different measures is relatively consistent, although the differences in the non-uniformity index values between U_4' and the others remains substantial.

COMPARISON BETWEEN MEASURES OF NON-UNIFORMITY COMPUTED FROM POINT-BASED AND AREA-BASED DATA STRUCTURES

18.01 The discrepancies between the measures of non-uniformity are observed not only within the set of measures computed from the same data, but also between two sets of measures computed from two differently struct-

ured data bases. Diagrams 5.25 - 5.28 show comparisons between the two sets of non-uniformity measures with indices computed for different block lengths and space sizes.

18.02 Diagram 5.25 shows the relationship between the different non-uniformity measures and space size at block length 1. The estimations of the non-uniformity index at this block length for the range of space sizes varies between 14% and 26%. The highest values of the non-uniformity index are shown by U_4' and the lowest by U_2. All eight measures agree on the position of highest non-uniformity index values at the smallest space size 1. They differ, however, in the position of the minimum values and in their pattern of behaviour in relation to change in space. Most of the measures fall slowly until they reach a minimum value at which they remain constant with further increase in spacing. A few of the measures increase slightly after reaching the minimum value. Within the range of values of non-uniformity indices some measures are closer to each other (within 2 - 3%) than others. This relationship divides the measures into fairly well defined groups with substantial differences in non-uniformity indices between them: U_1, U_2 and U_3 showing lower boundary values, U_1', U_2', U_3' and U_4 representing a middle band of non-uniformity index values, and U_4' as the measure with the highest values. The lowest value boundary is composed of point-based measures, while the middle group consists mainly of area-based measures. The highest value measure U_4' is an area-based non-uniformity measure.

18.03 When the block length is increased to 3, the measures of non-uniformity show differences in values, but a reasonable agreement in the overall pattern of behaviour in relation to change in spacing, diagram 5.26. The behaviour pattern is such that maximum values occur at space size 1,

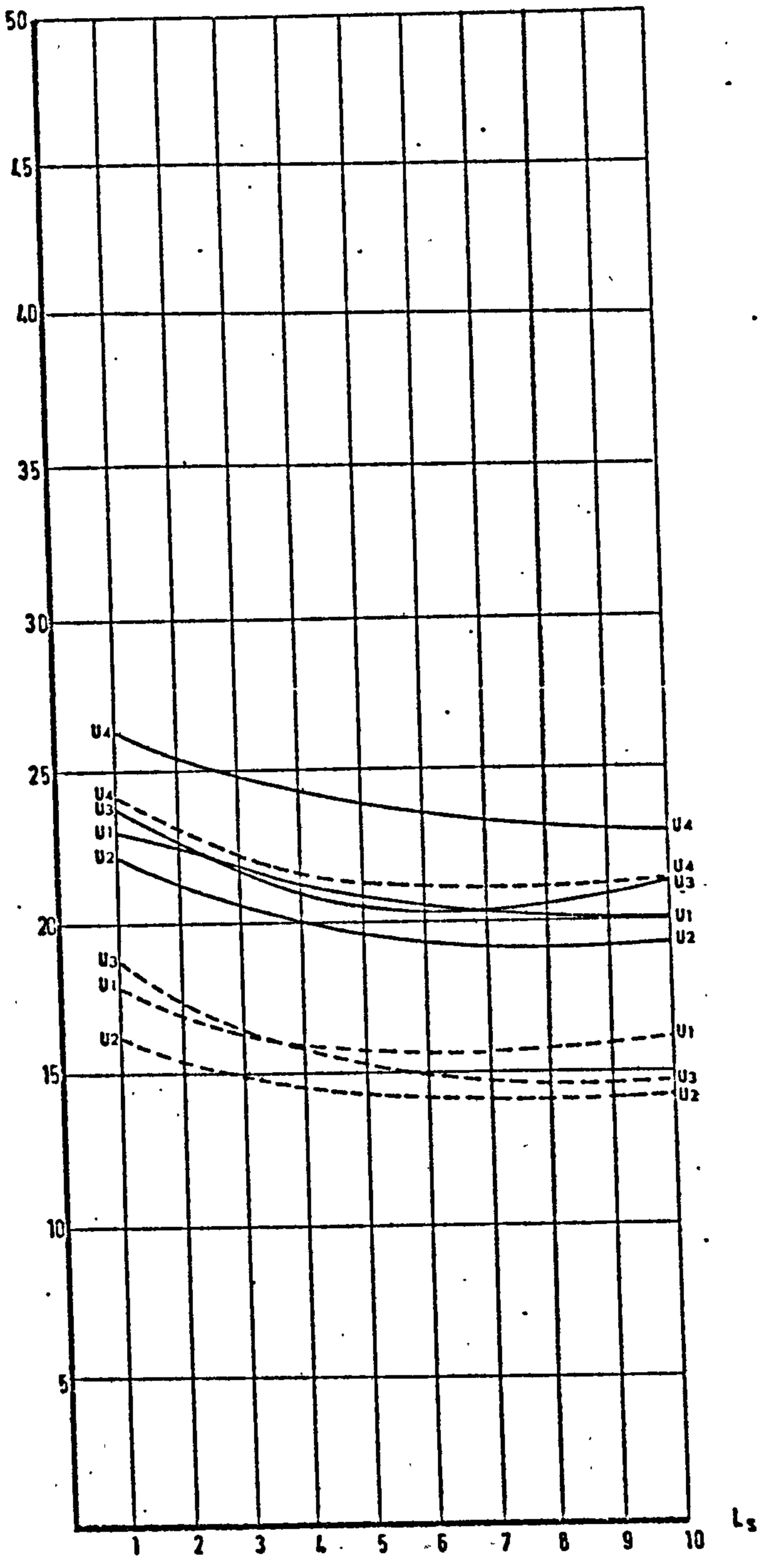


DIAGRAM 5.25: COMPARISON BETWEEN POINT-BASED (---) AND AREA-BASED (——) MEASURES OF NON-UNIFORMITY (BLOCK LENGTH 1 FOR DIFFERENT SPACE SIZES)

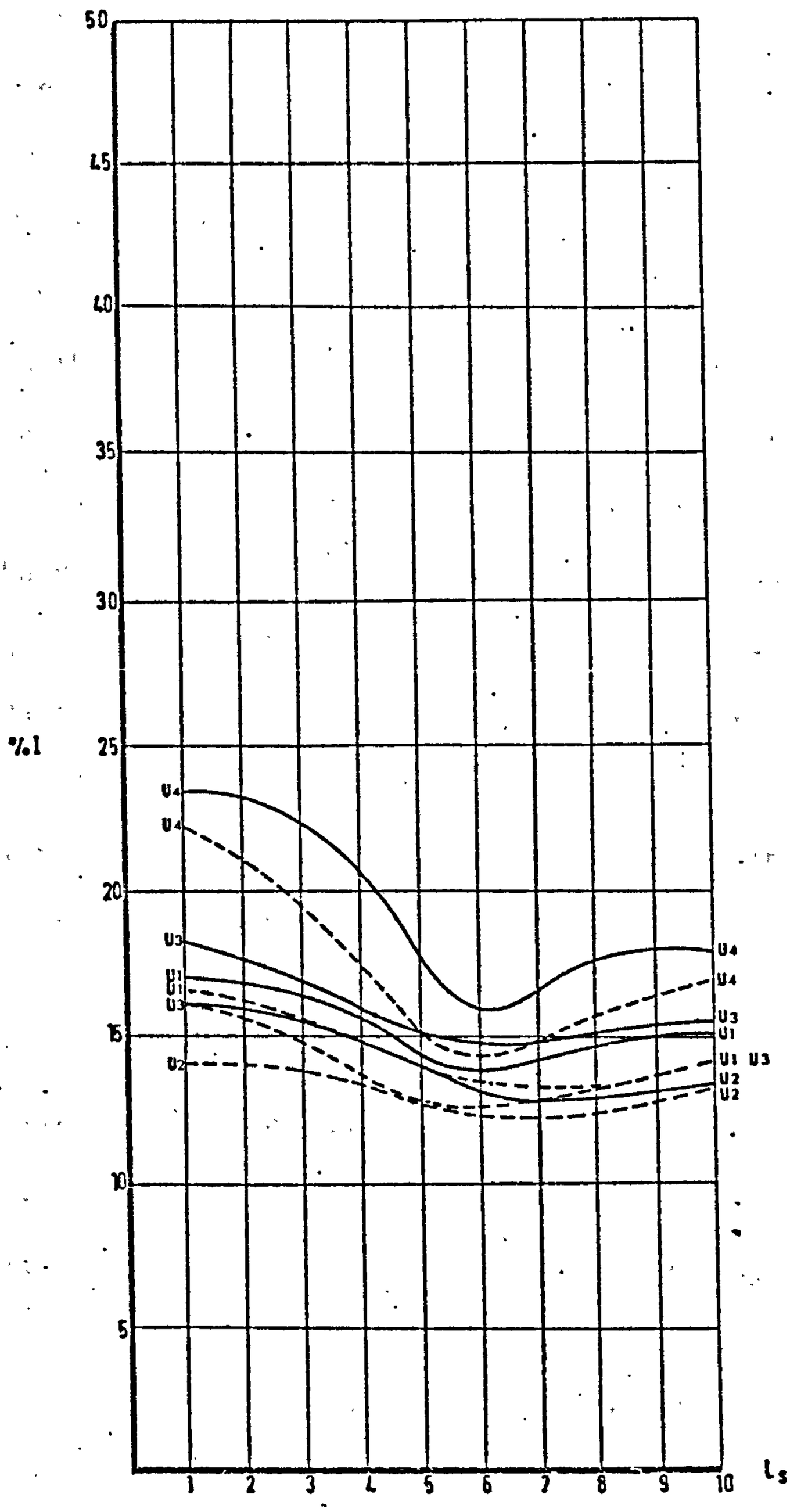


DIAGRAM 5.26: COMPARISON BETWEEN POINT-BASED (---) AND AREA-BASED (——) MEASURES OF NON-UNIFORMITY (BLOCK LENGTH 3 FOR DIFFERENT SPACE SIZES)

falling to a minimum at about space size 6 and increasing with further increase in spacing. The gradients of this change differ with different measures. For U_4 and U_4' it is relatively steep for most of the spacing range. For the others it is more gentle, e.g., U_2 shows non-uniformity indices to vary only within 2% for the whole space range, whereas U_4' varies within 7% for the same space range. The range of values within which non-uniformity indices are given by the different measures is 12% and it is less than that given in the previous block length. The highest values of non-uniformity indices are given by U_4' and the lowest are given by U_2. Measures U_1', U_2', U_3' and U_1, U_2, and U_3 constitute a relatively close band of values varying within 3 - 5% with substantial interference. U_4 and U_4' are closer to each other but at the position of minimum values, space 6, they come very close to the other measures. In this block length, therefore, the measures of non-uniformity, unlike in the previous case, spread their values relatively evenly within the range of index values, showing no clustering.

18.04 Diagram 5.27 shows a comparison between the measures of non-uniformity at block length 10 for different space sizes. The increase in block length has two effects on the non-uniformity measures:

a) it decreases their range of non-uniformity index values (10%), and,

b) causes them to spread relatively evenly within this range.

There is, however, a large interference in the index values among the different measures. As in the previous arrangements the highest values are shown by U_4', and the lowest values by U_2. The behaviour of the different measures with increase in space shows a number of discrepancies. In general, the maximum values of the non-uniformity indices occur at space 1, but the position of the minimum values differs. For some it

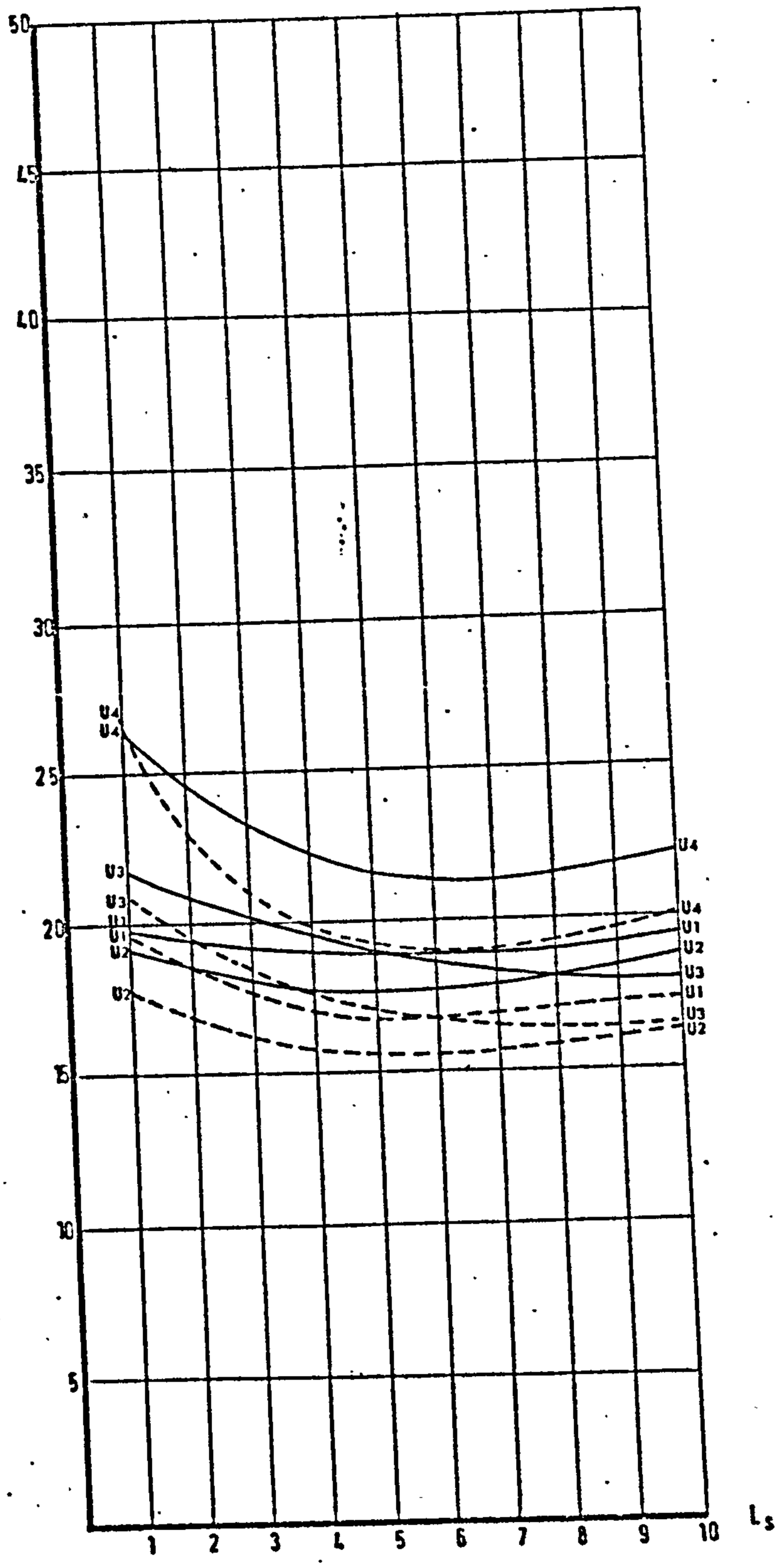


DIAGRAM 5.27: COMPARISON BETWEEN POINT-BASED (---) AND AREA-BASED (——) MEASURES OF NON-UNIFORMITY (BLOCK LENGTH 10 FOR DIFFERENT SPACE SIZES)

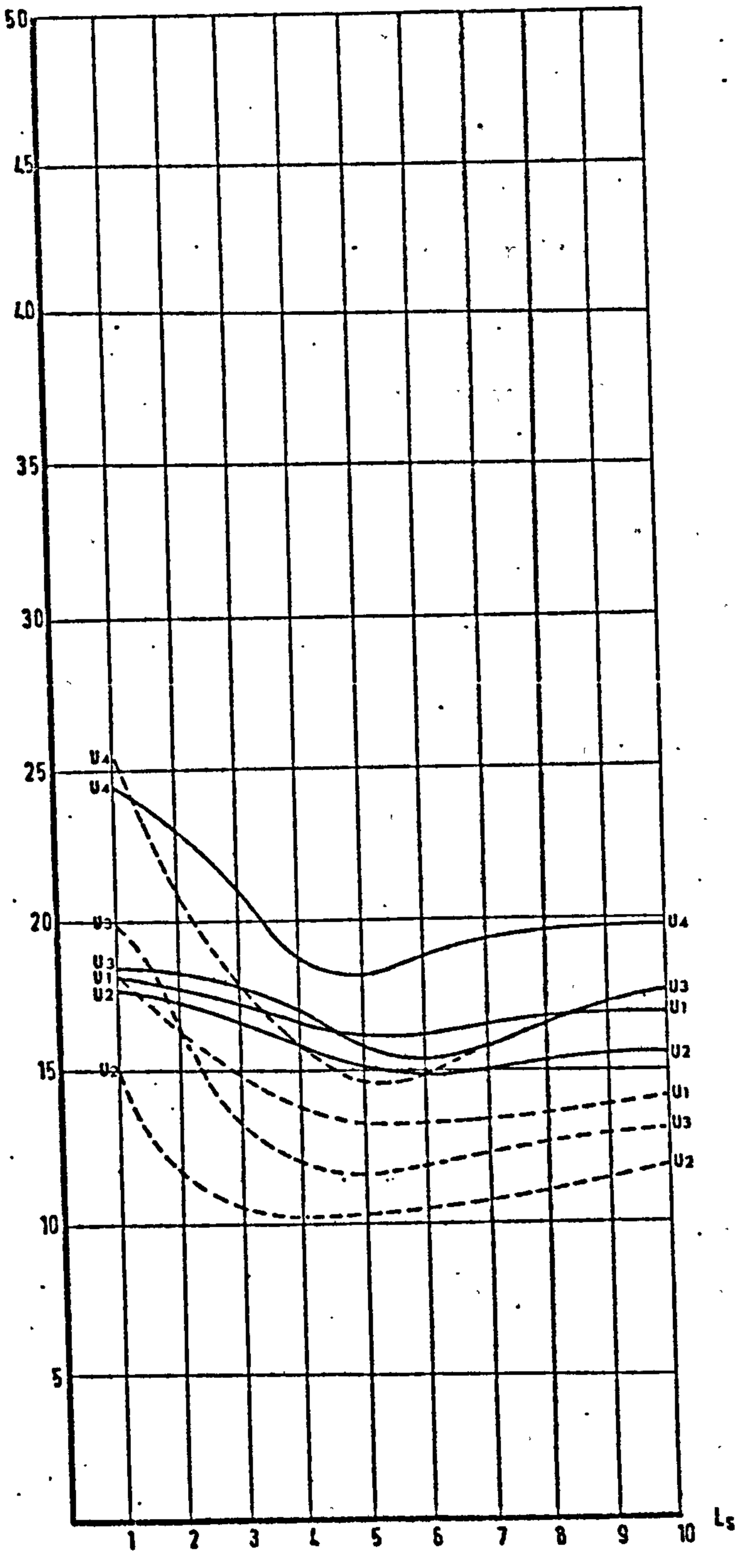


DIAGRAM 5.28: COMPARISON BETWEEN POINT-BASED (---) AND AREA-BASED (——) MEASURES OF NON-UNIFORMITY (BLOCK LENGTH 15 FOR DIFFERENT SPACE SIZES)

occurs around spaces 5 - 6 and for others it occurs around spaces 9 - 10. For some of the measures whose minimal values occur at the intermediate spaces, they remain at their minimal values, e.g., U_2, but others increase slightly beyond the position of minimal values.

18.05 At block length 15 the values of non-uniformity indices spread relatively more evenly over a wide range, diagram 5.28. The range of values in this case is the largest among all arrangements (15%). The highest values are shown by U_4' and the lowest values by U_2. The change in the non-uniformity index values shows two different features between the point-based measures and the area-based ones. The point-based measures show a relatively rapid drop in index value between space 1 and space range 3 - 5 with a slight increase after that. The area-based measures, except for U_4', show a very slow change towards the minimum, occurring at space 5.

SUMMARY OF DIFFERENCES BETWEEN THE MEASURES OF NON-UNIFORMITY

19.01 The indices of non-uniformity have been computed from measures of different formulations using different data structures. From the values they show and their pattern of behaviour in relation to form aspects, the following observations can be made:

a) measures of non-uniformity based on dividing grouped data geometrically (quartile and percentile ranges) show the lowest values of non-uniformity indices. Those based on computing individual deviations from the exposure index show relatively higher values of non-uniformity indices.

b) the geometric based measures of non-uniformity are far less sensitive to changes in the form aspects. They show small ranges and relatively gentle slopes as the form changes.

c) there are two distinct categories of measures with respect to the values of non-uniformity indices they yielded: the point-based measures and the area-based measures. The point-based measures give generally lower values relative to the values given by the area-based measures. This discrepancy can reach 10% difference in index values.

d) the area-based measures, despite the differences in their sensitivity to change in form, show a more consistent behaviour as the form changes. This is seen in relatively closer positions of minimum values and in the ranges within which index values remain stationary.

e) independent of the data structure, there is a relatively larger difference in index values between the measures U_4, U_4' on the one hand and U_1, U_2, U_3 and U_1', U_2', U_3' on the other. This difference is largest at smaller block lengths, but diminishes as the block length increases. Therefore, the values of the non-uniformity indices given by the measures spread more evenly over the range of index values at larger block lengths.

19.02 The differences amongst the non-uniformity measures are likely to result from three sources: the nature of the data structure, the sample size from which an index is computed and the formulation of the measures. In the following section, the effect of the sample size and data structure are studied for non-uniformity measures of different formulations.

THE EFFECT OF THE SAMPLE SIZE ON THE NON-UNIFORMITY MEASURES

20.01 In the preceding sections non-uniformity indices were computed from an initial sample measured at one unit grid (chapter IV). The sam-

ple, is either in the form of point measurements or interpolated into speed contours lines to give areas with representative velocities. The effect of the sample size on the index values, sensitivity and behaviour of the non-uniformity measures is studied by computing non-uniformity indices from two larger samples. The two samples are taken at half-unit grid and quarter-unit grid. They are indicated as sample a and sample b respectively.

20.02 The increase in sample size has no effect on the area-based non-uniformity measures. This is understandable since increasing the sample size does not influence the spatial distribution of the speed contours which define areas of specific uniform exposures (chapter IV). Therefore, the discrepancies between the area-based measures persist. This suggests that the disparities in their index values are solely due to their different formulations.

20.03 In the case of the point-based non-uniformity measures, the situation is quite different. The measures which are based on the geometric division of grouped data (inter-quartile and percentile ranges) show very small or no change with respect to increase in sample size. This situation pertains to the nature of the spatial distribution of the exposure in the different arrnngements and the formulation of the two measures. Invariably, throughout the forms studied, there exist two distinct regions of relatively high and relatively low exposure (velocity) values. The inter-quartile and percentile divisions happen to fall in these two regions, no matter what the sample size is. Increasing the number of readings in these two regions (as the sample size increases) does not appreciably diversify the exposure values within them. Therefore, when the data is grouped and divided geometrically to find the positions of the inter-quartiles and percentiles

within a region of almost uniform values, irrespective of sample size,and accordingly the non-uniformity index value remains constant, or shows very little change. Although it is negligible, any change is likely to be the result of the accompanying change of the relevant exposure index value.

20.04 The sample size has, however, a pronounced influence on two point-based measures of uniformity: U_4 and U_1. In diagrams 5.29 - 5.31 the effects of the sample size on measure U_4 are shown for a range of block lengths in relation to different space sizes. The sample size influences both the value of the non-uniformity index and the behaviour of the non-uniformity measure. The effect on the behaviour is illustrated in diagram 5.32 where the increase in index values is also accompanied by change in the slope of the curve. The curve of U_4 changes to resemble that of U_4' at sample b. It is significant that with increase in sample size the non-uniformity indices of U_4 increase to reach those computed by U_4' whose values do not change with sample size. This suggests that for a certain sample size, U_4 is not reliable and is, therefore, sensitive to the increase or decrease in sample size. U_4' due to its smaller sample size and its stability in relation to increase in sample size, is both reliable and economic in terms of its data requirements.

20.05 What happens in the comparison of U_4 and U_4' is also true when comparing U_1 and U_1'. The values of U_1 approach those of U_1' as the sample size increases, giving more or less the same non-uniformity index values at sample size b.

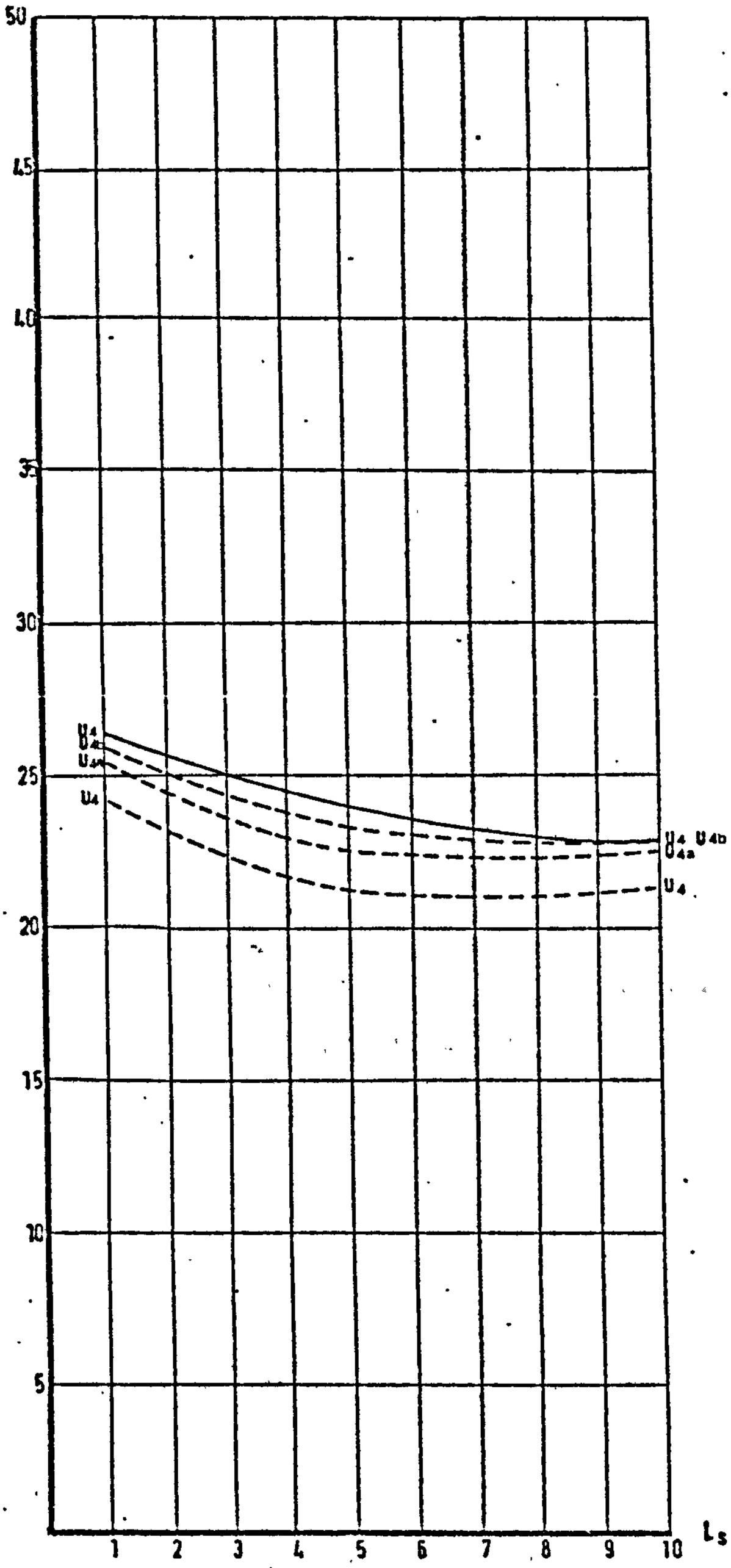


DIAGRAM 5.29: THE EFFECT OF SAMPLE SIZE ON NON-UNIFORMITY INDEX VALUES (AT BLOCK LENGTH 1 FOR DIFFERENT SPACE SIZES)

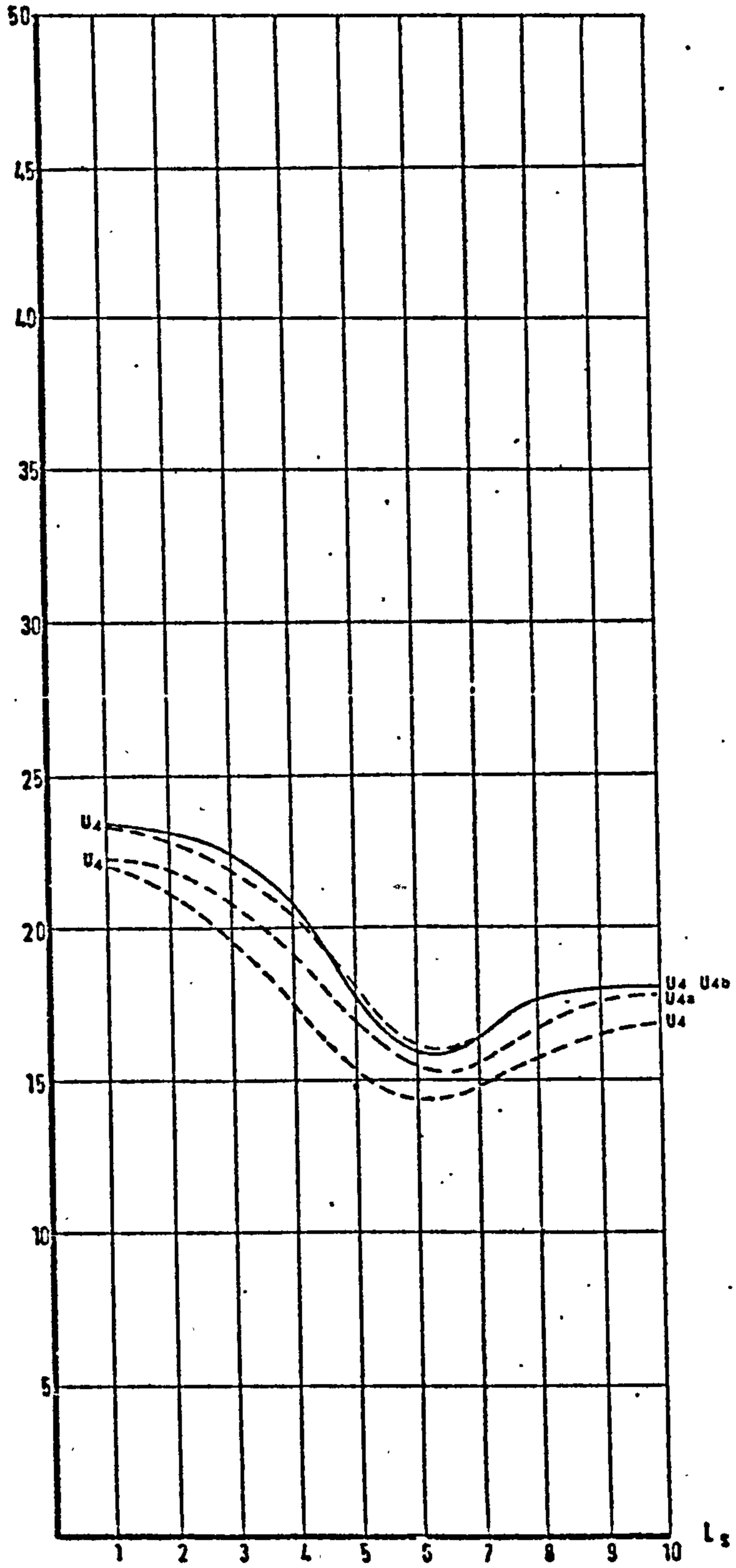


DIAGRAM 5.30: THE EFFECT OF SAMPLE SIZE ON NON-UNIFORMITY INDEX VALUES (AT BLOCK LENGTH 3 FOR DIFFERENT SPACE SIZES)

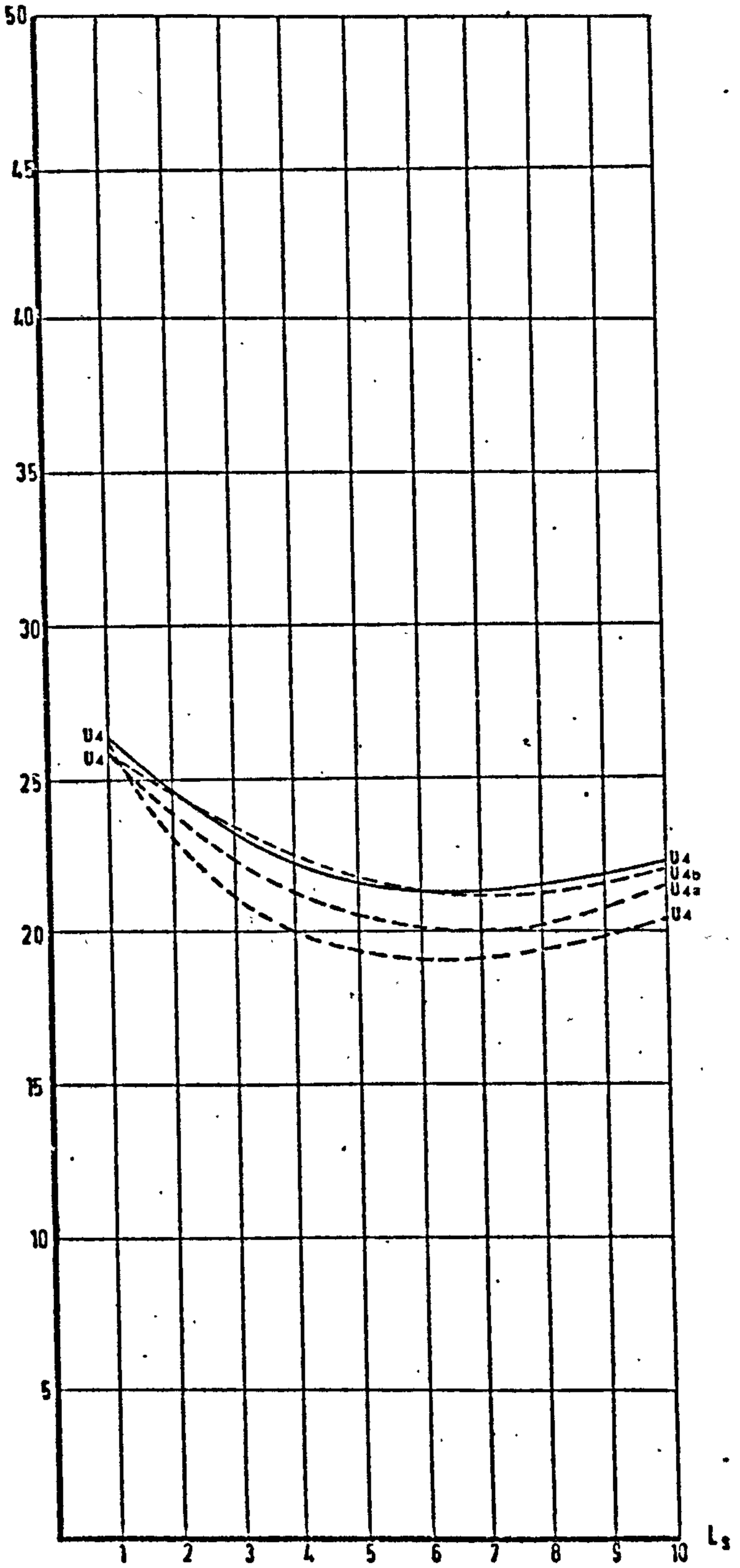


DIAGRAM 5.31: THE EFFECT OF SAMPLE SIZE ON NON-UNIFORMITY INDEX VALUES (AT BLOCK LENGTH 10 FOR DIFFERENT SPACE SIZES)

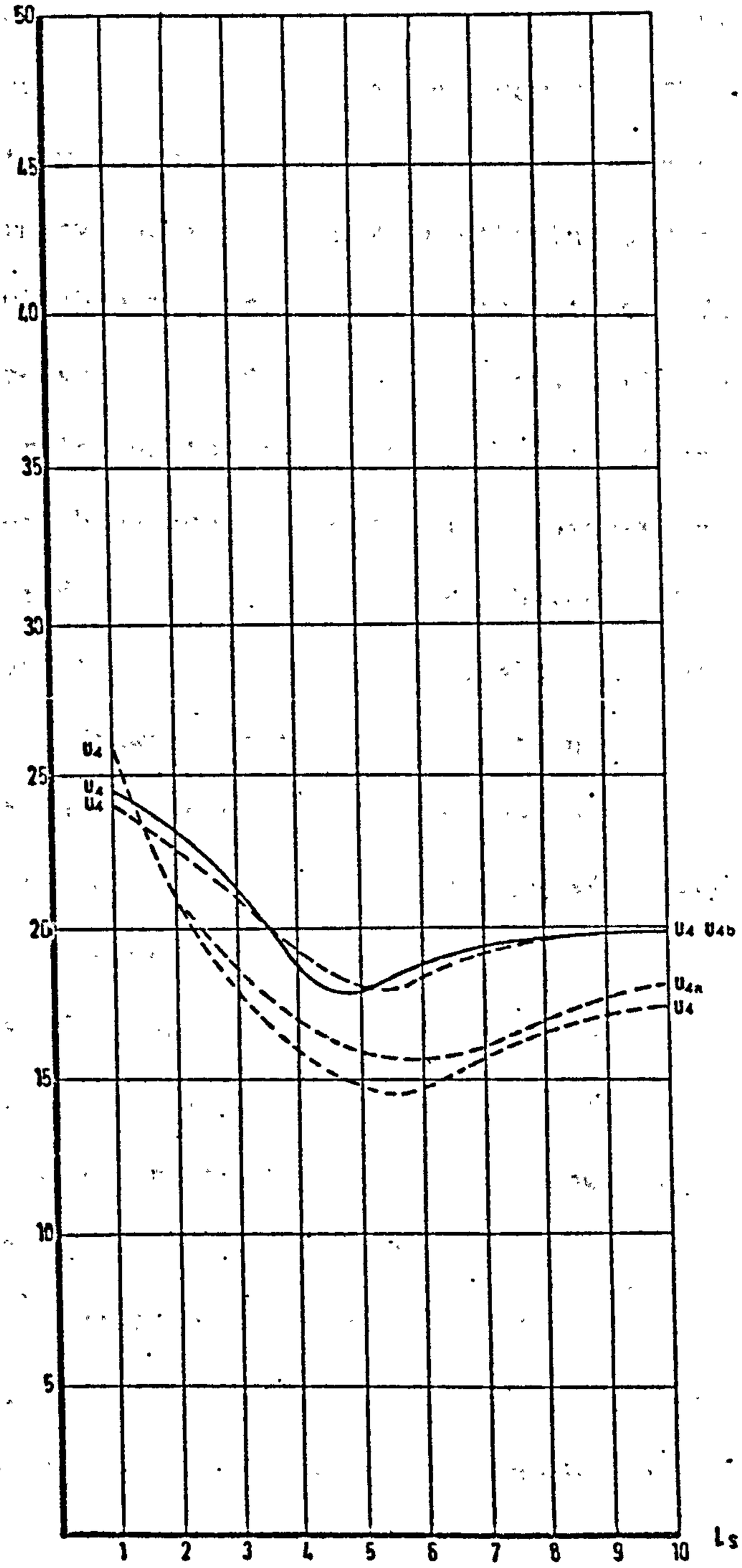


DIAGRAM 5.32: THE EFFECT OF SAMPLE SIZE ON NON-UNIFORMITY INDEX VALUES (AT BLOCK LENGTH 15 FOR DIFFERENT SPACE SIZES)

CONCLUSIONS

In the development of a measure to describe the non-uniformity of exposure in a given zone four possible measures were considered. The measures vary considerably in their formulation, data size and data structure required to compute a non-uniformity index. In differentiating and evaluating the measures to select a suitable measure of non-uniformity the data structure and the sample size were varied to determine the sensitivity of the measures and their stability in relation to these aspects. Attention was also focussed on changes in their behaviour in relation to changes in form. Two data bases were considered: point-based and area-based. Three sample sizes were used in computations of the non-uniformity indices. The following conclusions can be drawn from the investigations:

1. The formulation of the non-uniformity measures constitutes a source of large differences in the values of non-uniformity indices for the same arrangements.
2. The measures of non-uniformity are sensitive to the structure of the data. Computations of non-uniformity indices from a point-based data structure are generally lower than those computed from an area-based data structure.
3. The measures, due to the nature of the data base, and their formulation, show different sensitivity to changes in form. Those based on geometric division of grouped data (U_2, U_3) are rather sluggish and have relatively small ranges of index values, whereas the others (U_1, U_4) have relatively larger ranges and show more appreciable change in values (evident in steeper gradients), as the form changes.
4. Greater sensitivity to change in form is apparent in the case of computations from an area-based data structure, but less so

in the case of computations from point-based data structure.

5. The sample size has an appreciable, but variable influence on the values of the non-uniformity indices. It has no effect on the values computed from an area-based data. When comp-utations are made from point-based data the values from measures based on geometric division of grouped data (U_2, U_3) show very little or no change in values. The other two measures (U_1', U_4) show a substantial shift in non-uniformity indices with increase in sample size. The shift concerns the actual values of the indices and the behaviour of the measure in relation to change in form. The general pattern is that values computed from measures U_1 and U_4 increase with sample size until they come very close to or coincide with values computed from area-based measures, U_1' and U_4'. This suggests that the area-based comp-utations are stable in relation to sample size and are, therefore, more reliable and economic due to their sample size requirements.

6. From the above, it can be concluded that U_1' and U_4' are the most appropriate measures of non-uniformity. The differences between them, however, cannot be resolved, since it is largely due to their different formulations. In comparative and evaluative studies this discrepancy can be tolerated, provided that the same measure is used throughout. Since U_1' is less laborious in computation, it might prove of greater practical value.

C H A P T E R V I

THE DEVELOPMENT OF A MEASURE OF THE SPATIAL DISTRIBUTION OF EXPOSURE (THE EXPOSURE PROFILE AND THE LOCALISATION FACTOR)

1.00 INTRODUCTION

1.01 In the development of the quantitative-visual flow representation an important property in the representation was evident - it gave, in addition to depicting flow patterns, an idea about how the different zones within the space vary in their speed values as indicated by the speed contours. A useful measure of the flow can describe the change in exposure with distance from a given point of reference. This will be termed the exposure profile. Such a measure adds more qualification to the general statement about the exposure given by the exposure index.

PROPERTIES OF THE EXPOSURE PROFILE MEASURE

2.01 The exposure measure depicts a generalised property of a given space, whereas the exposure profile assigns continuous values of exposure to consecutive zones within the space, hence describing its spatial distribution and its variation with distance from a given reference point. In a sense, the exposure profile can act as a measure of variance, but it should be borne in mind that it is fundamentally different from the non-uniformity measure on account of its constituent spatial aspect. This property makes it of particular value in comparative and evaluative studies of form flow relationships. It has the special advantage of being of direct use in a design decision situation where each part or zone of the space considered has an exposure value associated with it and presented against other zones' values.

2.02 On account of its spatial component, the exposure profile can best be represented graphically where the relevant form and its profile are concomitantly depicted. However, for a wider application, especially in comparative studies, the use of two orthogonal axes, one denoting the

spatial component, e.g., distance from a given point,and the other denoting the exposure value, seem to be more appropriate. As will be seen in some cases special descriptors of the spatial component may be necessary for a comparative study. These have to be developed for the particular situation concerned. In this investigation, a special descriptor is developed to compare exposure profiles of different spaces.

2.03 A further transformation of the spatial distribution of the exposure is made possible by its representation as an exposure profile. This transformation is a numerical one describing the concentration of the highest exposure values within the space. It is termed the localisation factor. Its sensitivity to change in form makes it a useful descriptor in wind flow studies.

2.04 Another property of the exposure profile is that it reveals more readily the shifts in position of such characteristic values as the highest exposure values. This aspect also shows certain regularities with change in form and can, therefore, be of appreciable value in design.

COMPUTATIONS OF THE EXPOSURE COMPONENT OF THE PROFILE MEASURE

3.01 To assign a profile of exposure for a space, the space has to be divided into zones and the exposure of each zone computed. In Chapter IV it was found that the most reliable and sensitive measure of exposure was measure I_5, where

$$I_5 = \sum_{i=0}^{100} \left[\frac{a_i (V_i + V_{i+10})}{2} \right] \Big/ 100A$$

This measure of exposure is used to compute the exposure values of the sub-divided space.

THE SPATIAL COMPONENT OF THE PROFILE MEASURE

4.01 A space between two parallel blocks can be divided vertically or horizontally into a number of zones. Each zone has an exposure index which can be computed using I_5. Here, the space will be sub-divided vertically to assign a horizontal profile of exposure to it. The sub-division will depend on the rate with which the exposure changes along the space. Therefore a number of trial zones have to be attempted before the appropriate number is decided. In the cases investigated here, ten such zones were found to be a suitable range.

4.02 In the arrangements used, the spaces increase by 1 unit increments. This was the case for each of three orientations with respect to the wind. To compare the exposure profiles for each of the spaces for a given block length the spatial component of the profile has to be related to a common attribute of the different size spaces which is invariant under the change in size. This attribute pertains to the way the space is defined and its relationship to the direction of flow. Each space is created as a result of two blocks laid out such that one of them is upwind and the other is downwind. This aspect of the spaces is invarient under the change in size. Therefore, each space is bounded by a facade of the defining blocks which allows three topological regions of the space to be defined: an upwind region, a central axis and a downwind region. Similarly, the ten zones in which each of the spaces is defined are topologically equivalent and invariant under the change of

size. The two zones at the extremities of each space are appropriately named the upwind zone and the downwind zone and the central region is the central axis, diagram 6.1.

4.03 Using two orthogonal axes the vertical axis gives the value of the exposure index and the horizontal one defines the topological regions. On the horizontal axis three topological axes are shown defining the upwind zone (U_z), the central axis (C_a) and the downwind zone (D_z), diagram 6.2. This representation allows the comparison of the exposure profiles of the different spaces.

THE EXPOSURE PROFILES OF DIFFERENT BLOCK LENGTHS WITH CHANGING SPACE SIZES AND ORIENTATIONS

5.01 The greatest value of the exposure profile measure is in comparative studies and evaluation of forms once a common spatial attribute is defined. This will be demonstrated by the study of the exposure profiles of the range of block lengths in which both spacing and orientation to the flow change. Diagrams 6.3 - 6.13 show the exposure profiles for such arrangements. Each diagram represents profiles of one type of block length. It consists of three graphs, one for each of the orientations 0°, 30° and 45°. In each graph, the exposure profile is shown for a number of spaces, ranging from 1 unit to 10 units. The vertical axis shows exposure values between 0.40 to 1.00. The horizontal axis represents the topological space descriptor in which the limiting zones, the upwind U_z and the downwind, D_z, and the central axis, C_a, are marked.

5.02 Diagram 6.3a shows the exposure profile at different space sizes for block length 1 at orientation 0°. Spaces 1 and 2 show a symmetrical

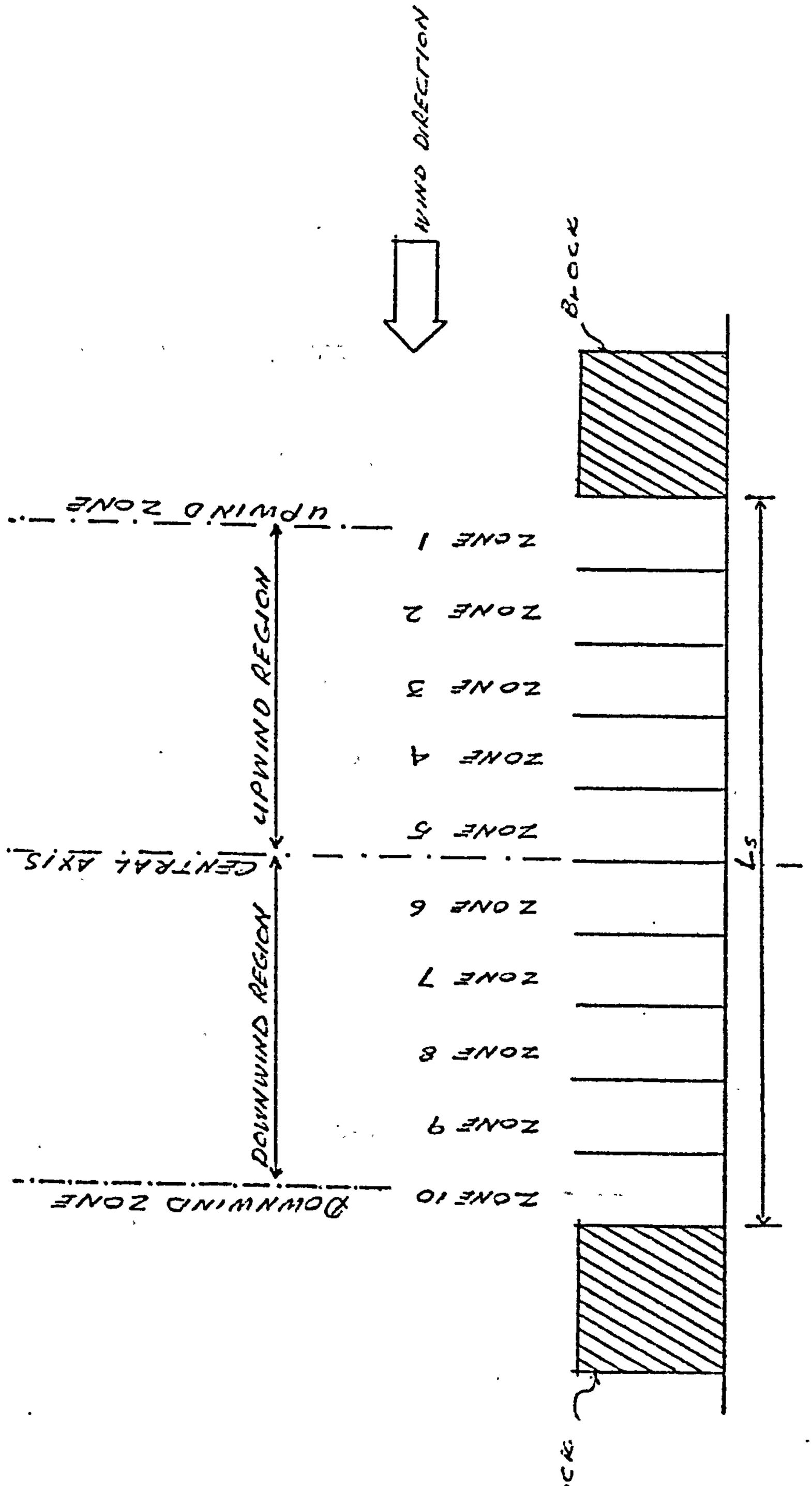


DIAGRAM 6.1: AN ILLUSTRATION OF THE TOPOLOGICALLY EQUIVALENT DIVISION OF SPACES OF DIFFERENT SIZES.

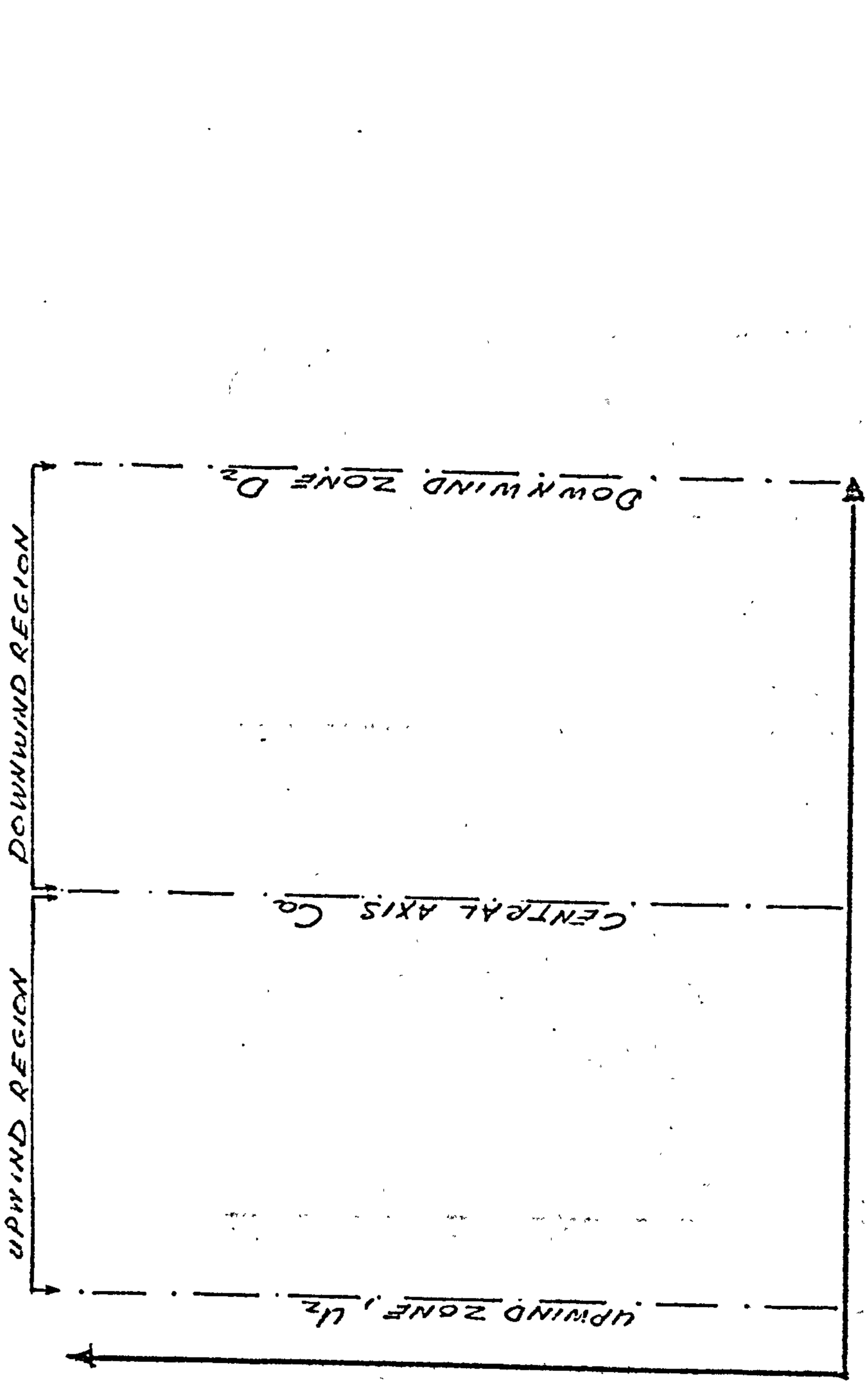


DIAGRAM 6.2: REFERENCE AXES OF THE DIAGRAMATIC REPRESENTATION OF THE EXPOSURE PROFILE.

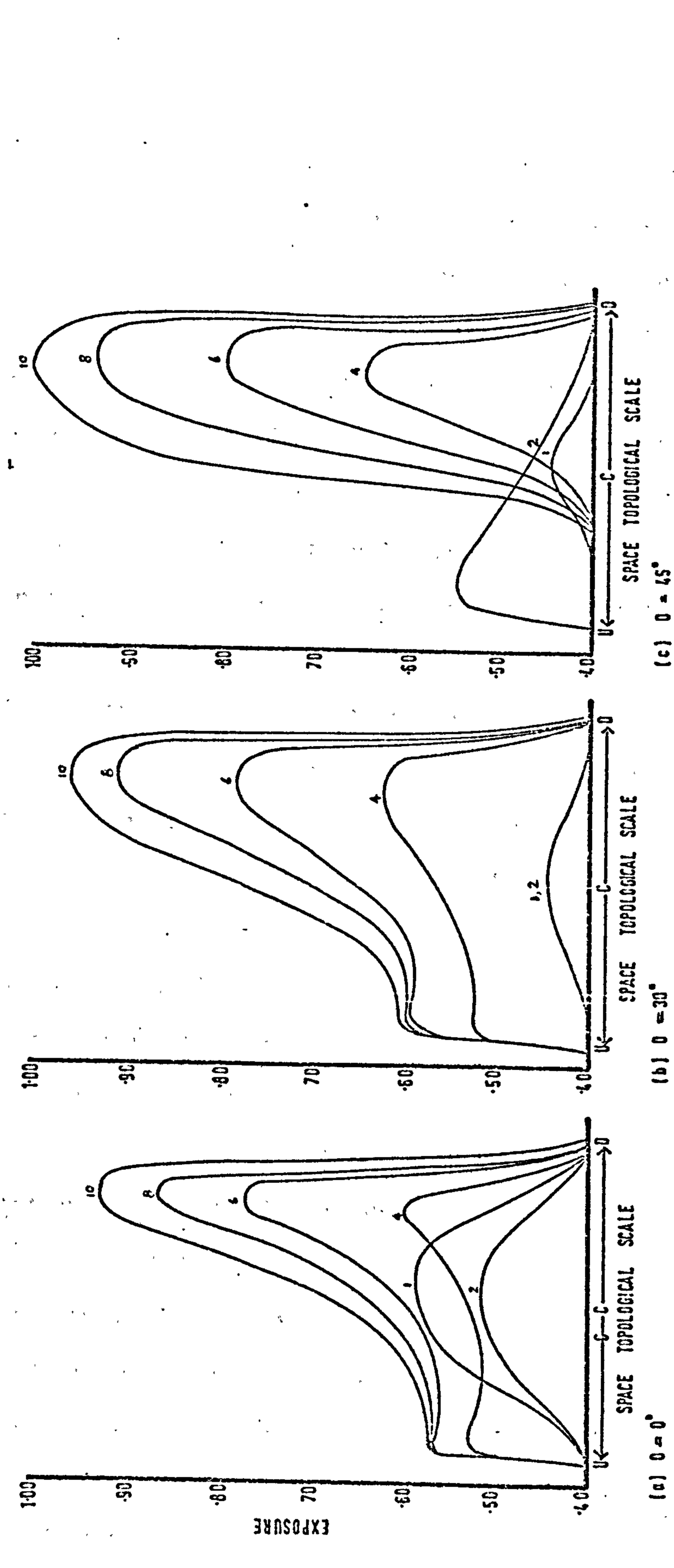


DIAGRAM 6.2: EXPOSURE PROFILES AT BLOCK LENGTH 1 FOR DIFFERENT SPACE SIZES AND ORIENTATIONS
(HORIZONTAL PROFILES)

exposure profile about the central axis with highest exposure occurring at the central axis. This maximum value is higher for space 1 than for space 2. Increasing the space size to 4 causes a steep increase in exposure nearer to the upwind zone. This drops slightly towards the central zone where it increases again to reach highest exposure around the centre of the downwind region. This shift of the position of the highest exposure zone is also shown by spaces 6, 8 and 10. These spaces have exposure profiles similar to that of space 4, except that the maximum values occurring at topologically equivalent zones, become higher the larger the space. The differences in exposure amongst spaces 4, 6, 8 and 10 are relatively small at the upwind zone, but increase towards the downwind zone and become largest at the zone of maximum exposure. It can be seen, therefore, that the increase in space has greater influence on zones on the downwind region than on those of the upwind region.

5.03 At orientation 30°, diagram 6.3b, for the same block length spaces 1 and 2 have approximately the same exposure profile. It is similar to the previous orientation in that it is symmetrical about the central axis where their maximum values occur. These values are much lower than in the previous orientation. The profiles of spaces 4, 6, 8 and 10 are structurally similar to those at the previous orientation, except that they are generally steeper and that of space 4 shows stationary exposure values in the upwind region. Maximum values are higher in this orientation but they occur at the same zone as in the previous orientation.

5.04 Diagram 6.3c shows the exposure profiles at orientation 45°. At this orientation, there are only two aspects of the exposure profile that are in common with the previous two orientations: space 1 has a profile symmetrical about the central axis and that spaces 4 - 10 have

the same position of maximum exposure values as in the previous orientations. There are two new features of the profile at this orientation. The first is that space 2 shows its maximum exposure value in the upwind region near the upwind zone. The second is that spaces 4, 6, 8 and 10 have relatively lower stationary exposure values in the upwind region, which increase almost abruptly towards the maximum. The three orientations show a steep drop after the maximum values to take exposure values in the downwind zone similar to those in the upwind zone.

5.05 The increase in block length from 1 to 2 brings along changes in the exposure profile affecting values and distribution of exposure at all three orientations. These are shown in diagram 6.4. The exposure profiles for the different spaces of block length 2 are shown in diagram 6.4a for 0° orientation. Spaces 1 - 4 have profiles which are symmetrical about the central axis with maximum exposure values at the central zone. The peak of the profile of space 4 is only slightly off the central axis, but spaces 1 - 4 can be regarded to be equivalent both in exposure profile and values of exposure. Space 6, although showing a maximum exposure just off the central axis and of equal value to that of spaces 2 - 4 but the profile section on the upwind region is markedly different.
In the upwind zone, there is a rapid increase in exposure which slows down for the rest of the zones, advancing steadily towards the maximum value. Spaces 8 - 10 show a closely similar profile to that of 6 at the upwind region. On the downwind region, however, their profile continues with an increase in exposure to reach maximum value around the central zone of the region followed by a sharp drop toward the downwind zone.

5.06 The most pronounced change in exposure profile occurs at space 4 when the orientation angle is increased from 0° to 30°. This is shown in

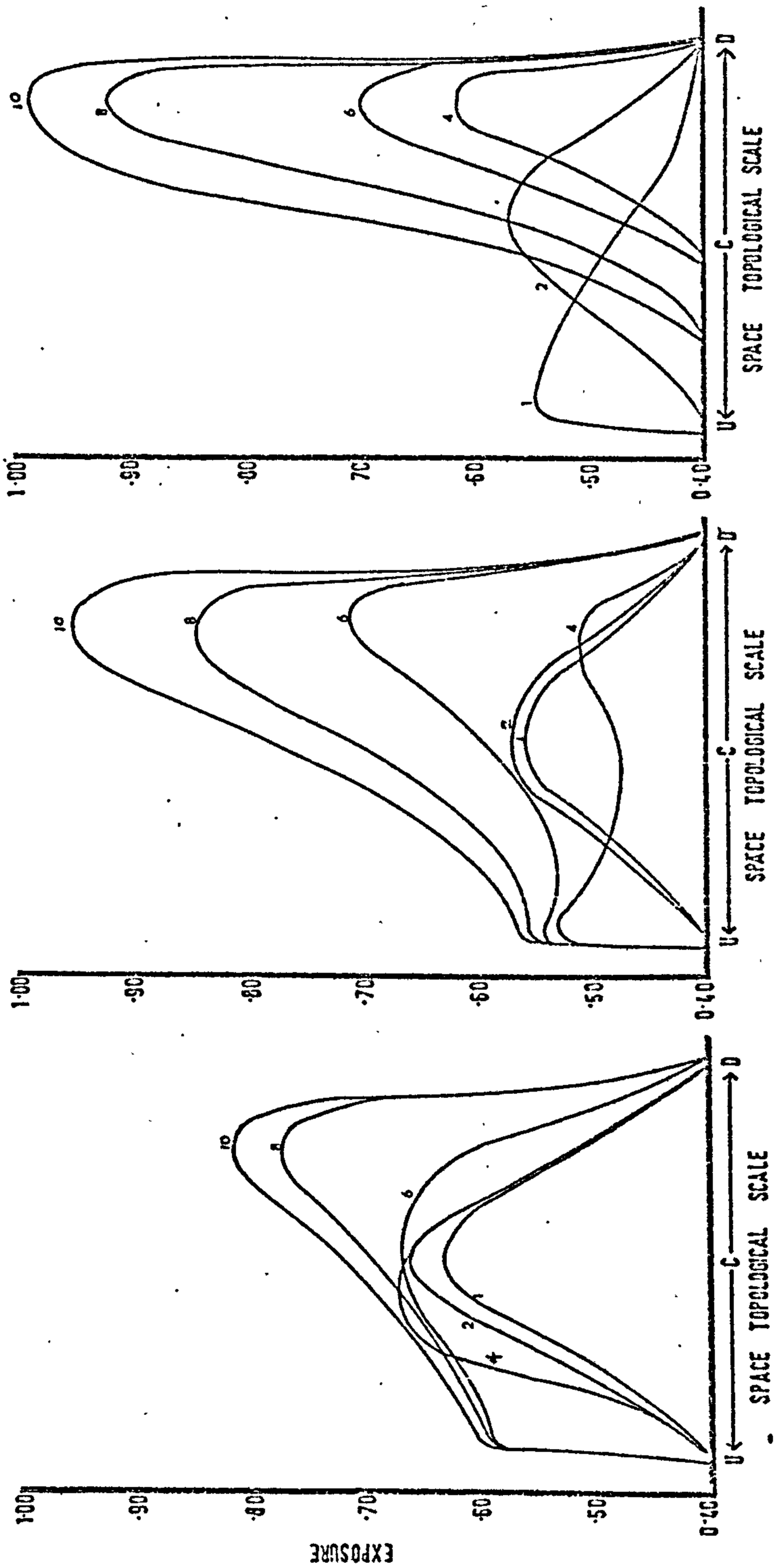


DIAGRAM 6.4: EXPOSURE PROFILES AT BLOCK LENGTH 2 FOR DIFFERENT SPACE SIZES AND ORIENTATIONS

diagram 6.4b. Space 4 shows a sharp increase to maximum exposure at the upwind zone decreasing steadily towards the central zone before it starts to increase towards the central downwind region. Beyond that point the exposure drops relatively rapidly towards the downwind zone. Spaces 1 and 2 have equivalent profiles, but they show lower maximum exposure values than in the previous orientations. Spaces 4 - 10 have structurally similar profiles, in that they show definite stages in their growth although differ in exposure values. They show a sharp increase in the upwind zone, followed by either a fall or statinnary value of varying extent and an increase towards the central zone of the downwind region before they rapidly fall towards the downwind zone. Spaces 6 - 10 have their maximum values around the central zone of the downwind region.

5.07 The exposure profiles of the different spaces of block length 2 are shown in diagram 6.4c for orientation 45°. Spaces 1 and 2 have reversed profiles to those of the same size in the corresponding orientation of block length 1. Space 1 shows a rapid increase towards the maximum at the upwind zone and a steady decrease towards the downwind zone. Space 2 has a symmetrical profile about the central zone with the maximum exposure value at the central zone. Spaces 4 - 10 show the same profiles as their counterparts in the previous block length, but only lower in values.

5.08 At block length 3, diagram 6.5, the exposure values are generally lower and the profiles show marked changes from the previous cases. At 0° orientation spaces 1 - 4 show the same profiles as in block length 2, but space 6 shows a shift towards the upwind region. Spaces 8 - 10 have lower exposure values than spaces 2 - 6 on the upwind region. Their

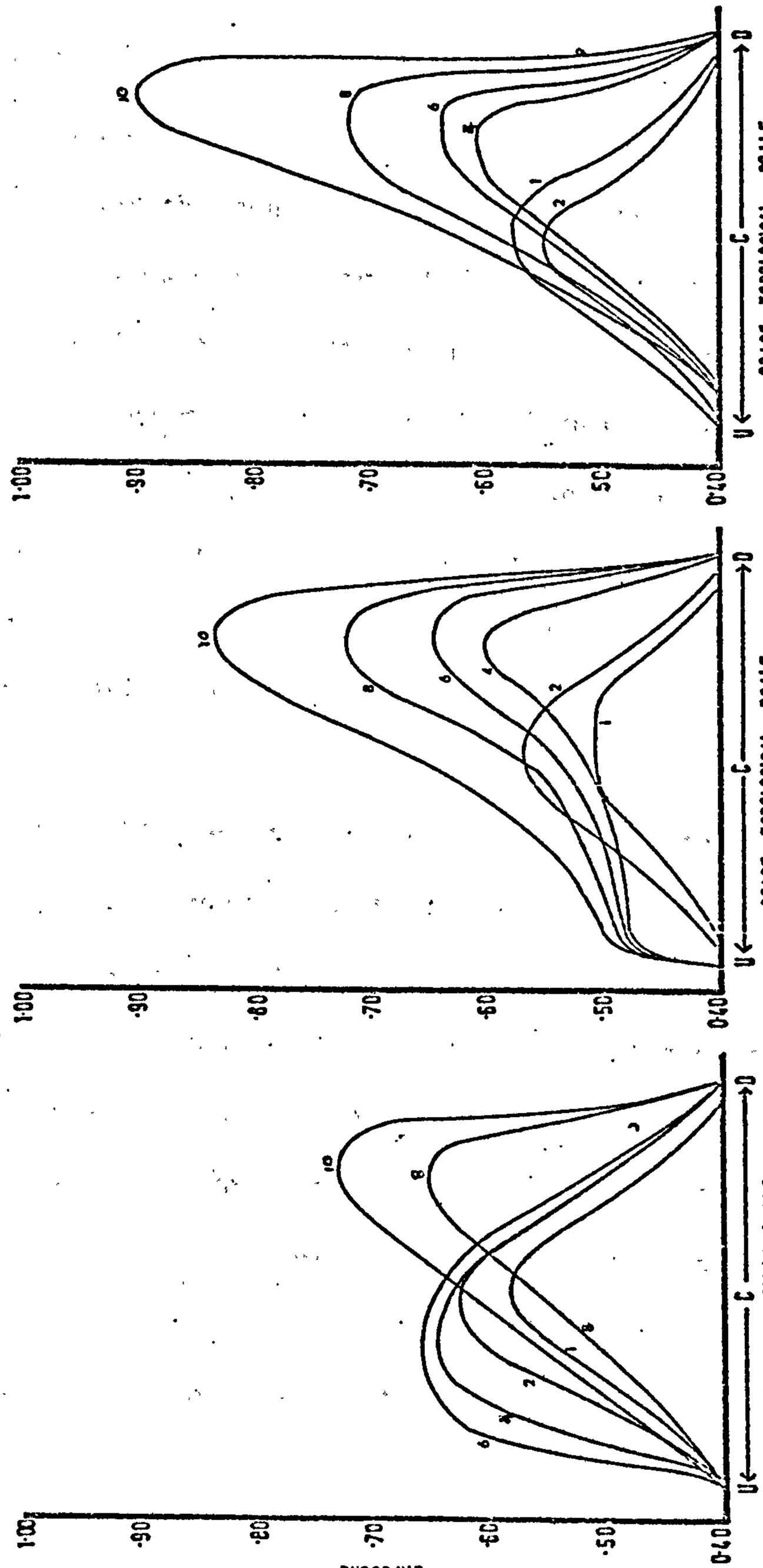


DIAGRAM 6:5: EXPOSURE PROFILES AT BLOCK LENGTH 3 FOR DIFFERENT SPACE SIZES AND ORIENTATIONS (HORIZONTAL PROFILES)

profile shows a less steep growth towards the maximum which occurs in the centre of the downwind zone.

5.09 Increasing the orientation angle to 30° brings greater similarities in the profiles of spaces 4 - 10, while the profiles of spaces 1 - 2 remain symmetrical about the centre with maximim exposure at the central zone. Spaces 4 - 10 show a rapid growth in exposure value at the upwind zone which slows down towards the central zone. In the downwind region their profiles are relatively steep with maximum exposure values around the centre of the downwind region. Between the maximum value zone and the downwind zone there is a sharp drop in exposure values. In the space range 4 - 10 the larger the space the steeper the profile, and the larger its exposure values.

5.10 At orientation 45° the space range of block length 3 also shows two distinct profile types. Spaces 1 and 2 have profiles symmetrical about the central axis. Spaces 4 - 10 show a steady growth in exposure values towards the maxima which occur around the central zone of the downwind region and then a rapid decrease in values towards the downwind zone. In general, spaces 4 - 10 have lower exposure values in the upwind region than spaces 1 and 2 but much higher values in the downwind region.

5.11 On increasing the block length to 4, diagram 6.6, the exposure profiles for spaces at orientations 0° - 30° show marked differences in shape and value from the previous block length. At orientation 0°, diagram 6.6a, the main changes in profile occur at spaces 6 - 10 with no basic changes for spaces 1 - 4. Spaces 6 - 10 show two peaks around the centres of the upwind and downwind regions, with a depression in between. The differences in the exposure values at the two peaks decrease with

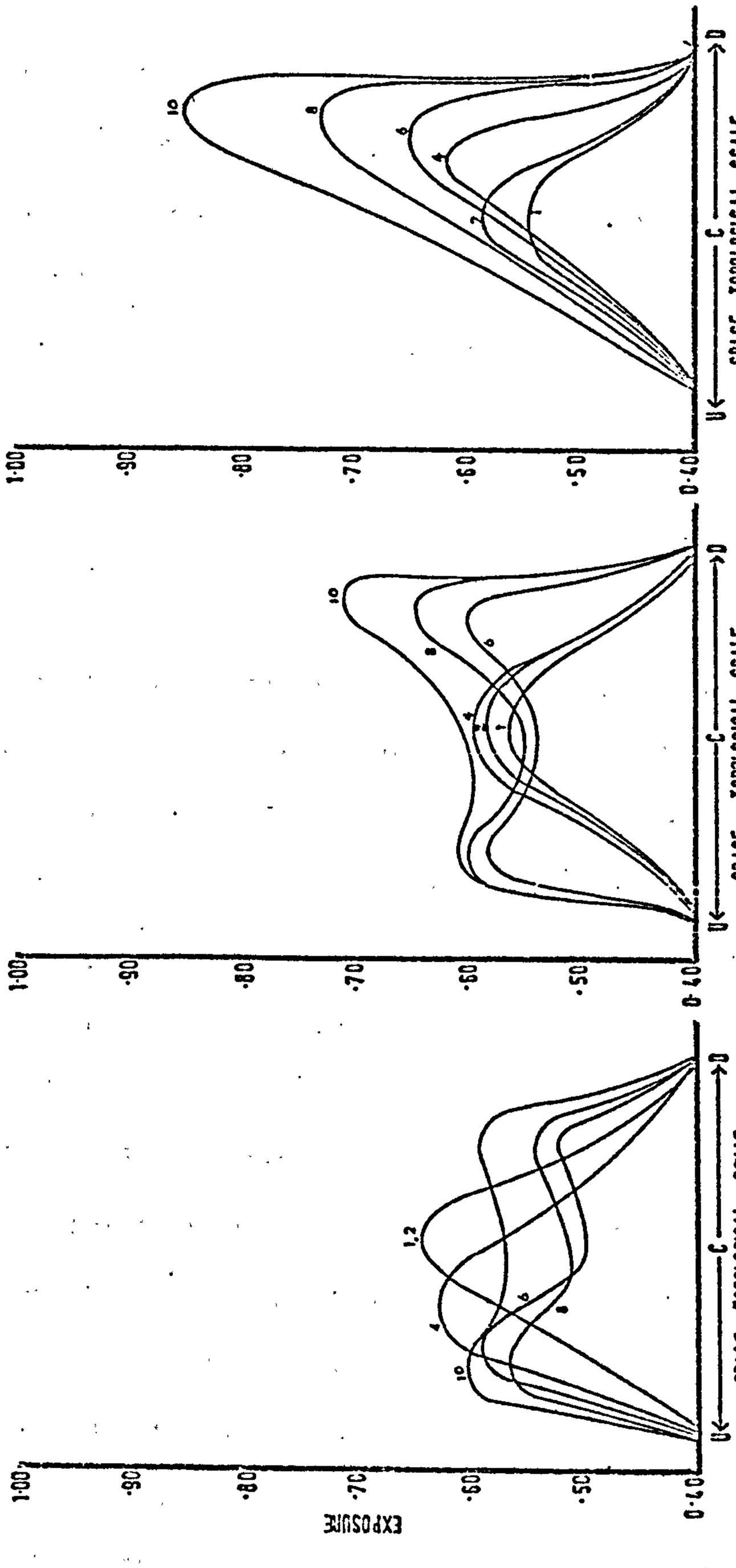


DIAGRAM 6.6: EXPOSURE PROFILES AT BLOCK LENGTH 4 FOR DIFFERENT SPACE SIZES AND ORIENTATIONS
(HORIZONTAL PROFILES)

increase in space, and the exposure values are usually higher at the upwind region.

5.12 At orientation 30°, diagram 6.6b, the profiles of spaces 6 - 10 are similar to those at orientation 0° in that they show two peaks and a depression in between. The differences, however, are in the position of highest exposures and range in the peak values. The highest values of exposure occur at the centre of the downwind regions. The differences between the two peak values for each spacing increase with the space size. Thus, the differences are smallest at space 6, larger at space 8 and highest at space 10.

5.13 The change in the exposure profile at orientation 45°, diagram 6.6c, at this block length, concerns the values, but not the shapes of the profiles. It is, therefore, different from the changes in the previous two orientations. Spaces 1 - 2 have a profile symmetrical about the centre of the space, while spaces 6 - 10 show a profile with a peak at the centre of the downwind region.

5.14 At block length 5, diagram 6.7, the exposure profiles undergo still more changes for orientations 0° - 30°. At orientation 0° the profiles of spaces 1 - 2 remain symmetrical about the centre of the space. The profiles of spaces 4 - 10 show a single peak at the upwind region, and stationary exposure values for most of the downwind region with the centre of the space as a transitional zone between the peak values and the stationary values. While the stationary values for any space increase with increases in space sizes, the peak values remain constant and are not affected by increases in space size.

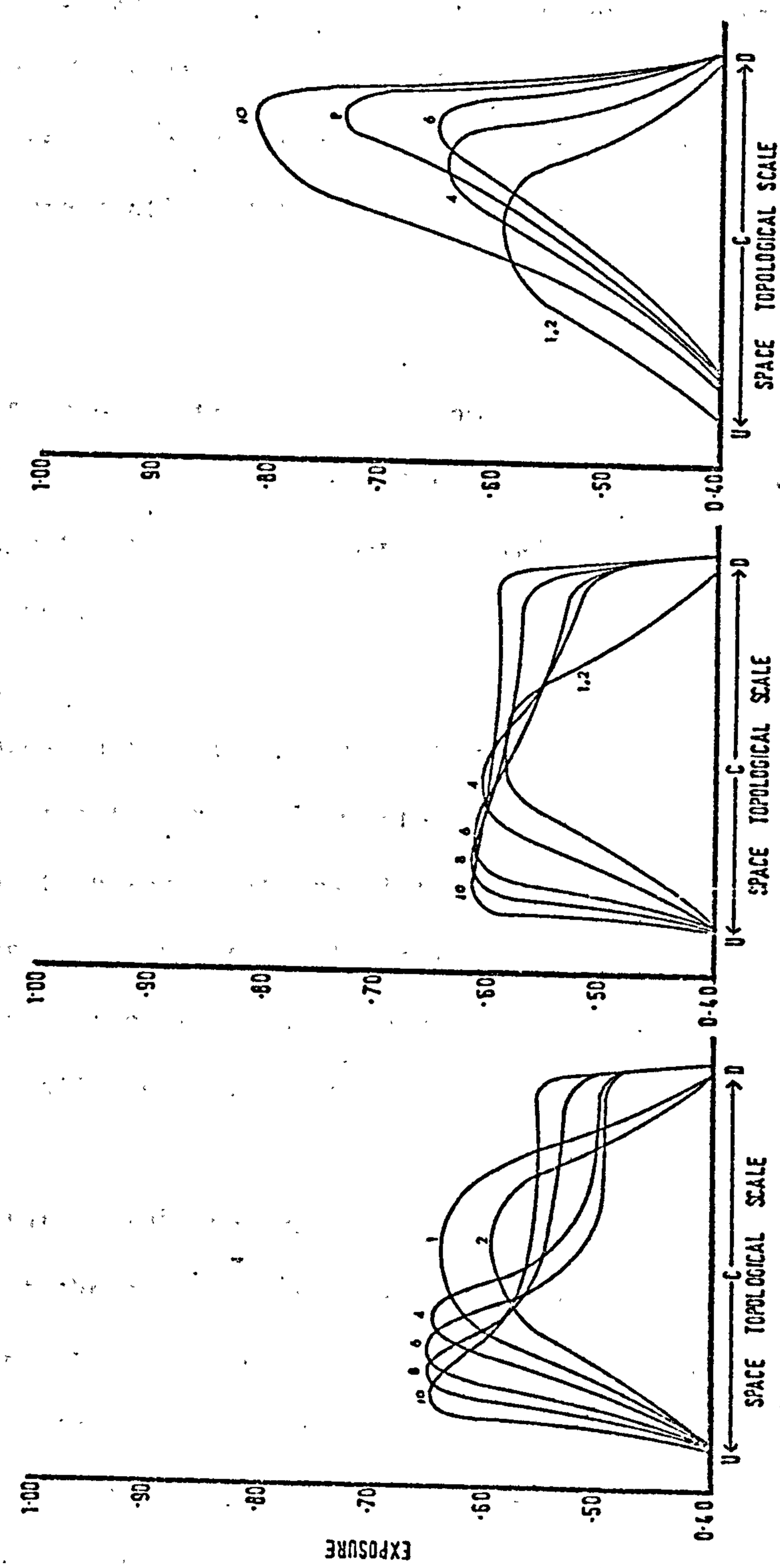


DIAGRAM 6.7: EXPOSURE PROFILES AT BLOCK LENGTH 5 FOR DIFFERENT SPACE SIZES AND ORIENTATIONS (HORIZONTAL PROFILES)

5.15 At orientation 30°, diagram 6.7b, the profiles show basically the same pattern as in the previous orientation. For spaces 4 - 10, however, the peaks are less conspicuous and the differences between their values and those of the stationary values are relatively very small. The exposure values of the different profiles are generally smaller than in the previous oreintation at the upwind region, but higher on the downwind region.

5.16 The exposure profiles remain the same with only changes in values at orientation 45°. The gaps in the exposure values narrow and spaces 4 - 6 have the same maximum exposure values, but with slightly different positions.

5.17 The changes in the profiles when the block length is increased to 6, diagram 6.9, affect all three orientations. At orientation 0°, spaces 1 - 2 show a shift in the positions of their maximum exposure values to the downwind region. Spaces 4 - 10 show peaks in their profiles at the upwind region but no stationary values at the downwind region - instead, exposures fall steadily towards the downwind zone.

5.18 At orientation 30° the exposure profiles of spaces 1 - 2 remain symmetrical about the centre. Spaces 4 - 8 show profiles with peaks at the upwind region and a steady drop towards the downwind zone. At space 8, however, there is a short range of stationary values at the downwind region. This increases to give a second peak at space 10, whose profile becomes characterised by two peaks and a depression in between.

5.19 At orientation 45° spaces 4 - 6 show the same pattern of the pre-

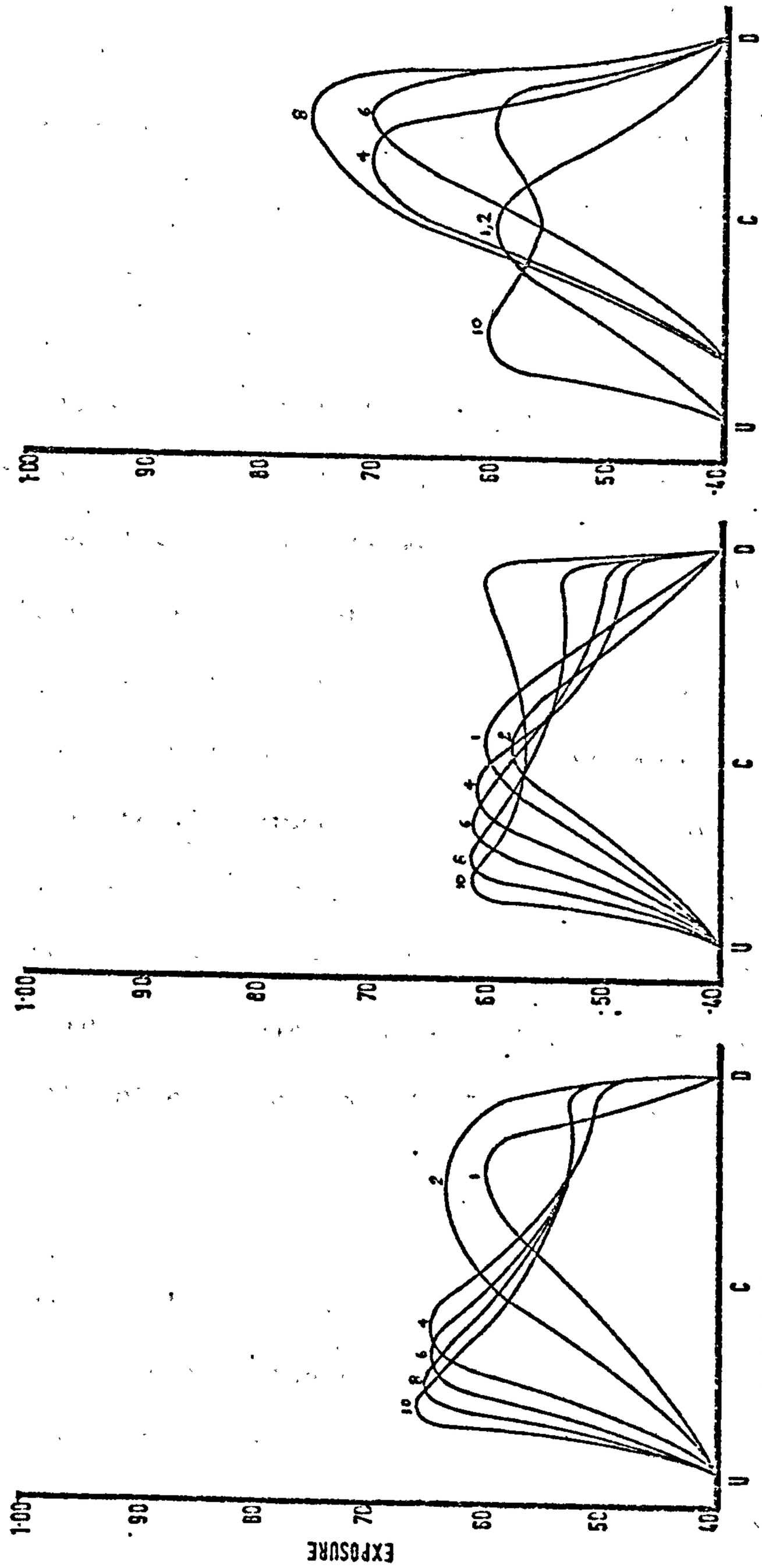
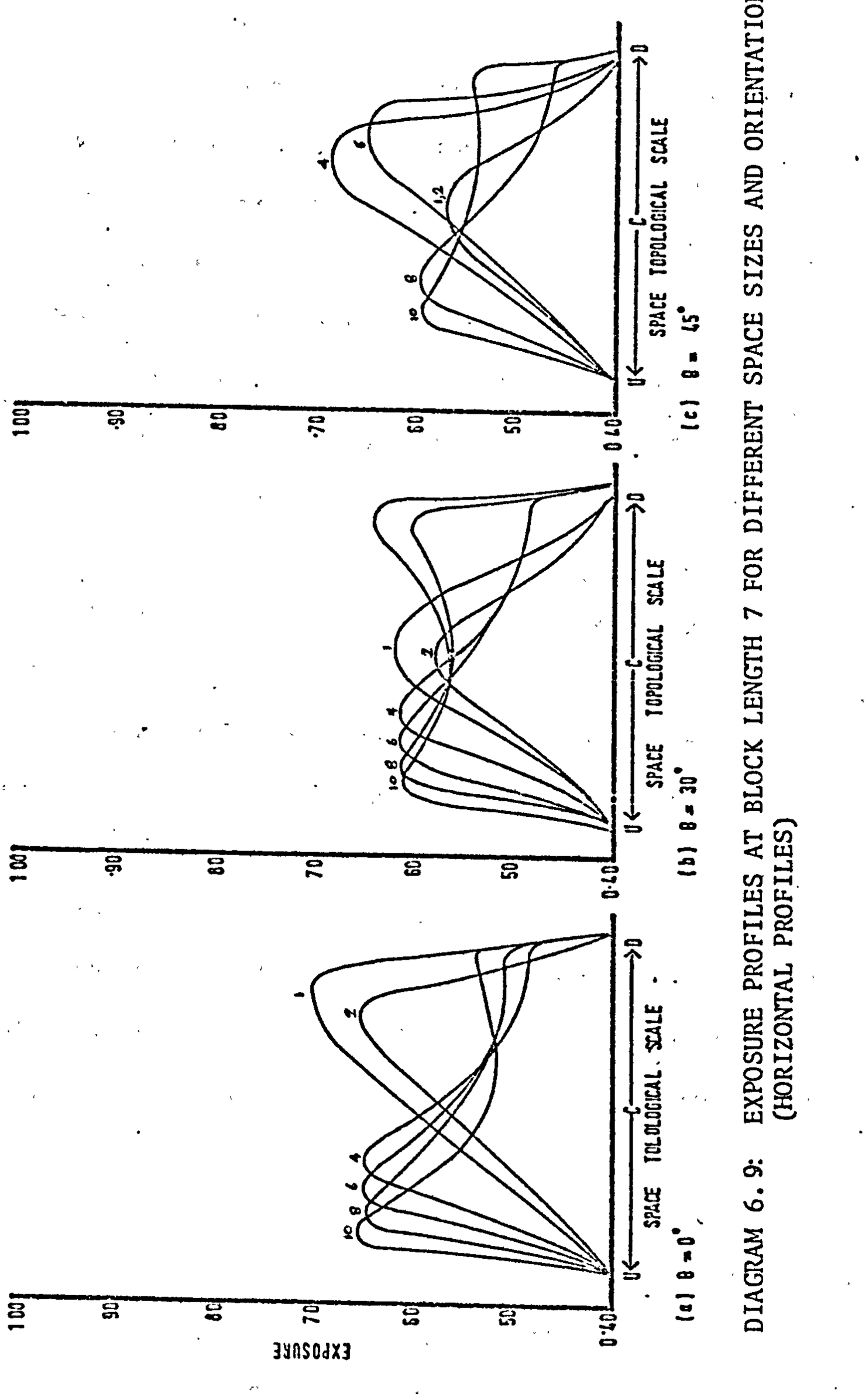


DIAGRAM 6.8 : EXPOSURE PROFILES AT BLOCK LENGTH 6 FOR DIFFERENT SPACE SIZES AND ORIENTATIONS
(HORIZONTAL PROFILES)

vious profiles at this orientation but with much smaller or no differences in exposure values. The main change in profile occurs at space 10. This shows a more or less symmetrical profile with equivalently positioned peaks at the upwind and downwind regions with lower values in between. This seems to be rather inconsistent with previous results for this arrangement, but it constitutes the beginning of a pattern manifested in all the remaining blocks.

5.20 Diagram 6.9 shows the exposure profiles at different spaces of block length 7 for the three orientations. At orientation 0°, diagram 6.9a, the exposure profiles at the different spaces are much the same as those for the previous block length at the same orientation. Spaces 1 -- 2 shift the positions of their highest exposure values to the downwind region. Spaces 4 - 10 show peaks in their exposure profiles at the upwind region and fall steadily towards the downwind region. There is, however, a change in the profile at space 10. After a steady fall towards the central zone, there is a slight increase in exposure values towards the downwind region. This is an exceptional tendency which is not shown by any of the other block lengths for the same space and orientation.

5.21 At orientation 30°, the exposure profiles show little change with this increase in block length. The changes, however, concern the profiles of spaces 8 - 10. These two spaces show two peaks: one in the upwind region and the other in the downwind region with relatively lower exposure values in between. At space 10 the downwind peak has a higher value than the upwind one, but at space 8 the highest exposure value is at the upwind peak. Spaces 4 - 6 show one peak of equal values and located at the upwind region. Spaces 1 - 2 have profiles symmetrical about



EXPOSURE PROFILES AT BLOCK LENGTH 7 FOR DIFFERENT SPACE SIZES AND ORIENTATIONS
(HORIZONTAL PROFILES)

DIAGRAM 6.9: E

the centre.

5.22 The largest changes in exposure profiles at this block length occur at orientation 45°, diagram 6.9c. Spaces 8 - 10 show equal value peaks at the upwind region, but, while space 8 profile falls steadily towards the downwind zone, space 10 profile shows 4 stationary exposure values beyond the centre of the space and for most of the downwind region. Spaces 4 - 6 show a steady growth in their exposure profiles to reach maxima at the centres of their downwind regions. Space 4 profile has a higher maximum than that of space 6. Spaces 1 - 2 show the same profile - symmetrical about the centre of the space.

5.23 Increasing the block length to 8 brings still more changes in the exposure profiles of the different spaces at different orientations, diagram 6.10. At diagram 6.10a the spaces range show only three profile types at orientation 0°. Spaces 1 - 2 have a steadily growing profile with maximum values around the centres of their downwind regions. Spaces 4 - 8 show a profile with a peak at the centre of the upwind region falling steadily towards the downwind region. Space 10 has basically the same profile as spaces 4 - 8, but the peak is achieved nearer to the upwind zone, and it has higher values for most of the upwind and downwind regions.

5.24 At orientation 30°, diagram 6.10b, spaces 1 - 2 have profiles which are symmetrical about the centre with space 1 having higher values. Spaces 4 - 6 have profiles with one peak at the upwind region, falling steadily towards the downwind zones. The peak of space 4 profile is nearer to the centre of the space than that of space 6. Spaces 8 - 10 have similar profiles with two peaks, one in the upwind region and the

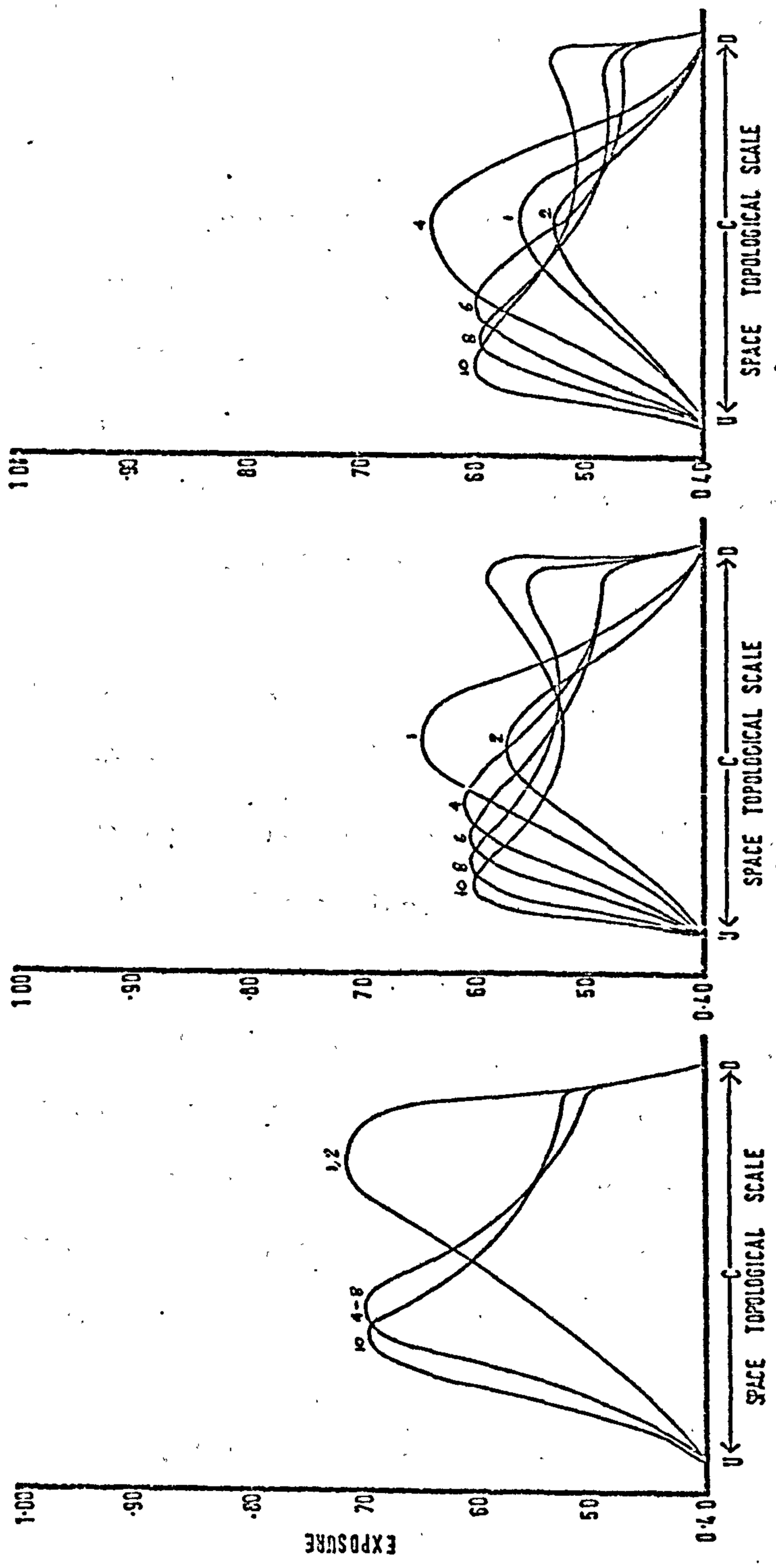


DIAGRAM 6.10: EXPOSURE PROFILES AT BLOCK LENGTH 8 FOR DIFFERENT SPACE SIZES AND ORIENTATIONS
(HORIZONTAL PROFILES)

other in the downwind zone, with much lower values in between. While their values are very near at the upwind region, the profiles of spaces 8 - 10 show a relatively large difference at the downwind peak with space 10 having a higher peak value.

5.25 Spaces 1, 2 and 4 have symmetrical profiles about the centre at orientation 45°, diagram 6.10c. Spaces 6 - 8 show more or less similar profiles with peaks at the upwind region and falling steadily towards the downwind zone. Space 10 has a slightly different profile from those of spaces 4 - 8. It has two peaks at the upwind and downwind regions with the upwind peak having a higher value.

5.26 Diagram 6.11 shows the exposure at block length 9 for different space sizes and orientations. At orientation 0°, diagram 6.11a, there are two main profile types. One shows a steady growth towards a maximum around the centre of the downwind region. This profile characterises spaces 1 and 2. The other profile type shows a rapid increase towards a maximum in the upwind region and a relatively slow fall towards the downwind zone. It is characteristic of spaces 4 - 10. The different spaces, however, (in the range 4 - 10) show different positions of peak values in the upwind region. The smaller the space the nearer its profile peak to the centre.

5.27 At orientation 30°, there are three profile types, diagram 6.11b: an exposure profile symmetrical about the centre, characteristic of spaces 1 - 2; a profile with a peak at the upwind region, spaces 4 - 6; and a profile with two peaks, one at the upwind region and the other at the downwind region, spaces 8 - 10.

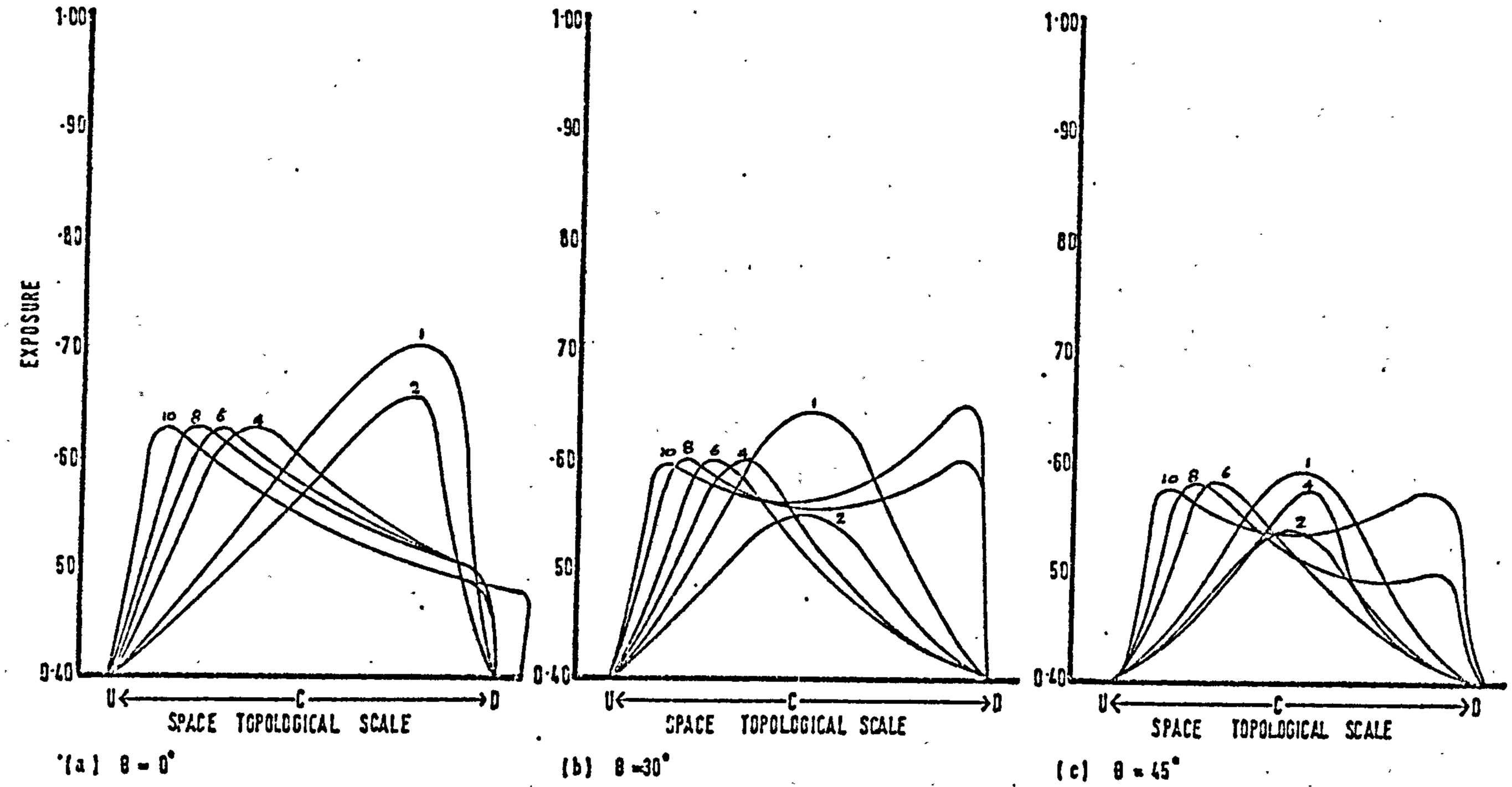


DIAGRAM 6.11: EXPOSURE PROFILES AT BLOCK LENGTH 9 FOR DIFFERENT SPACE SIZES AND ORIENTATIONS (HORIZONTAL PROFILES)

5.28 At orientation 45°, the same three profile types as at the previous orientation occur, but with lower values and shifts in the positions of highest exposures. Spaces 1 - 4 have profiles symmetrical about the centre, whereas space 6 shows a profile with a peak at the upwind region, falling relatively slowly towards the downwind zone. Space 10 shows two peaks in its profile with equal values and lower values in between. There is a fourth profile type shown by space 8. This shows a peak at the upwind region, nearer to the centre than that of space 10, and a stationary value for most of the downwind region. In this, space 8 has a similar profile to its profile at block length 8.

5.29 At block length 10, diagram 6.12, the main changes in the profiles concern the relative positions, occurrence and values of the peaks.
At orientation 0°, spaces 1 - 2 show no or very little change from their profiles at the previous block length. Spaces 4 - 10 show profiles with peaks at the upwind regions, falling relatively rapidly to take stationary values for the larger part of the downwind region. The positions of these peaks are much closer to each other and to the centre than at the previous block length for the same orientation.

5.30 Diagram 6.12b shows the exposure profiles at orientation 30°.
Spaces 1 - 2 have profiles which rise steadily towards maximum values at the downwind regions. Spaces 4 - 6 show profiles with peaks at the upwind regions and stationary values at the downwind regions. Spaces 8 - 10 have profiles characterised with two peaks at the downwind and upwind regions with the downwind peaks having higher exposure values. The differences between the upwind and downwind peak values are higher for this block length than at the previous block length for the same orientation.

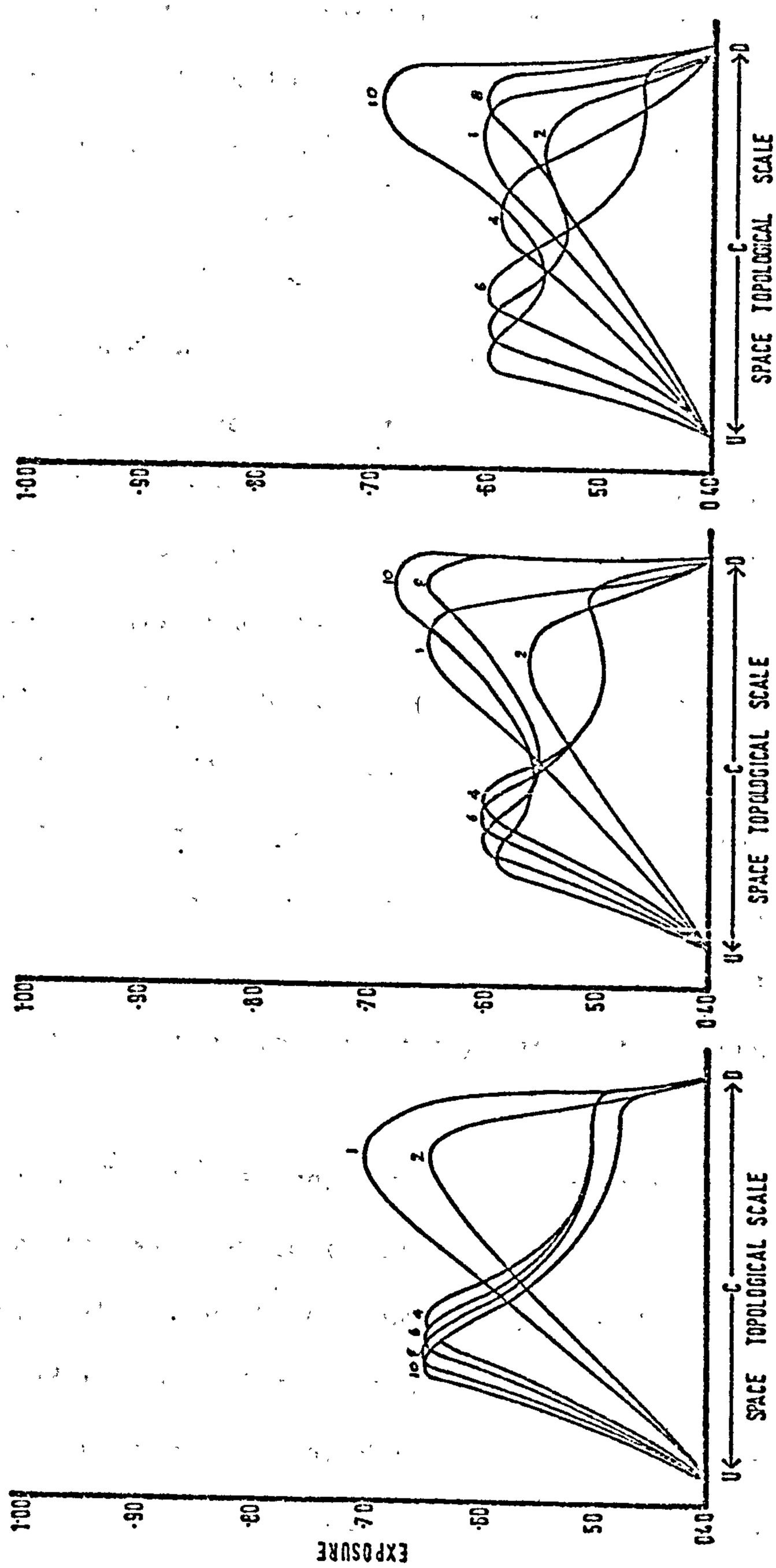


DIAGRAM 6.12: EXPOSURE PROFILES AT BLOCK LENGTH 10 FOR DIFFERENT SPACE SIZES AND ORIENTATIONS (HORIZONTAL PROFILES)

5.31 At orientation 45°, diagram 6.12c, the profiles are basically similar to those in the previous orientation, except for space 4, which has a profile symmetrical about the centre. There are, however, slight differences as to the values and positions of the peak values. The downwind peak values of spaces 8 - 10 show a marked increase over those of the previous block length for the same orientation.

5.32 The exposure profiles in the block length range 11-20 show relatively small variations. Here only those of block length 15 are described and they are considered representative of this range of block lengths. The exposure profiles at block length 15 for different space sizes and orientations are shown in diagram 6.13. The profiles are characterised by relatively low values, especially at orientation 45°.
At orientation 0° there are three profile types: the first is a profile symmetrical about the centre for space 1. Space 2 has a profile with a maximum value at the centre of the downwind region. The third profile type is shown by spaces 4 - 10 and it consists of a peak at the upwind region and a relatively large stationary segment at the downwind region.

5.33 At orientation 30° the spaces range also shows four profile types. The first two types are similar to those of spaces 1 and 2 at the previous orientation. The third type, shown by spaces 4 - 6 consists of a peak at the upwind region and relatively stationary values at the downwind region. The fourth type of profile has two peaks at the upwind and downwind regions, with lower values in between. This profile type is shown by spaces 8-10.

5.34 The same set of profile types is shown at orientation 45°, diagram 6.13c, by the same space sizes. There are, however, slight differences

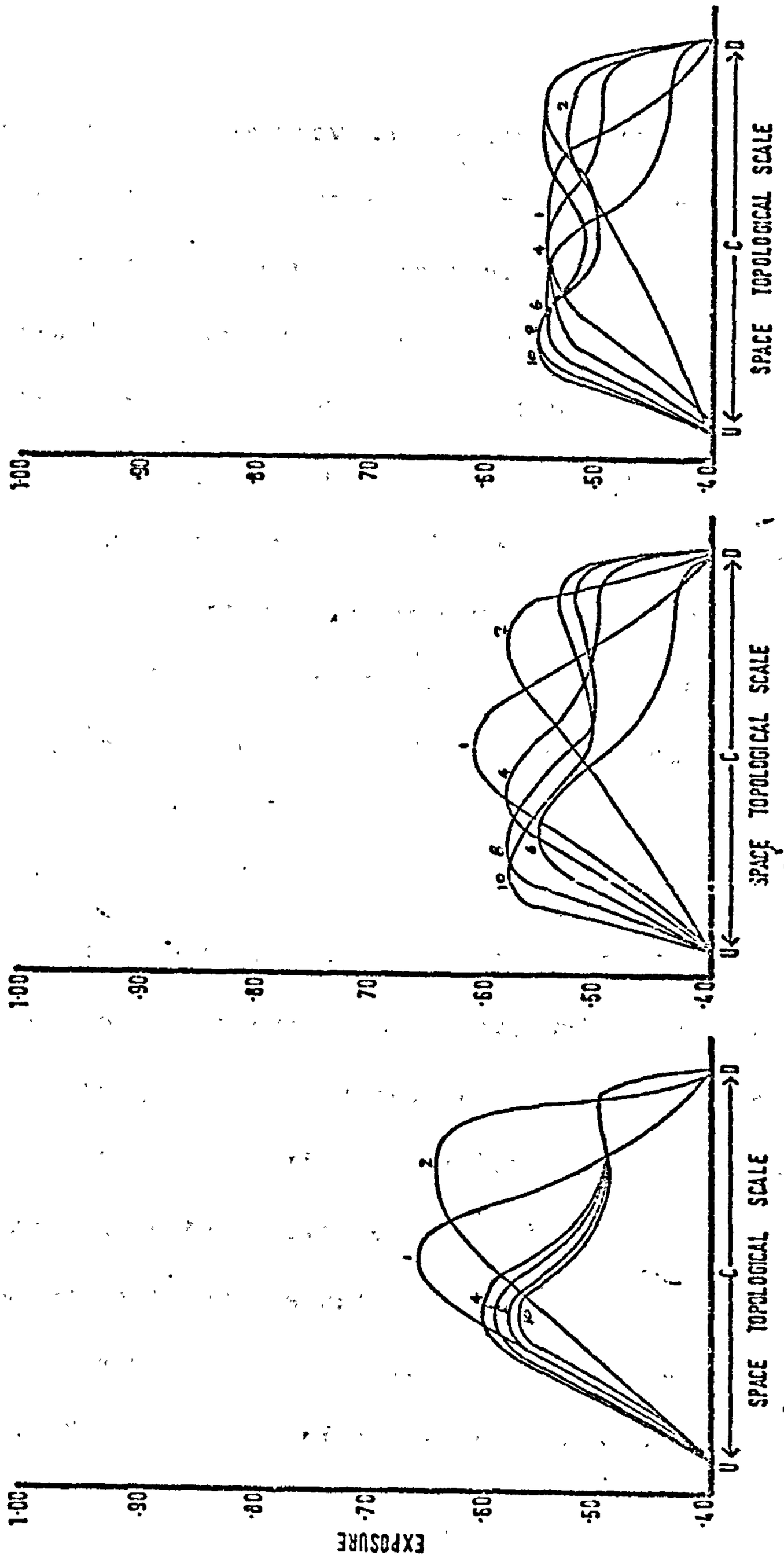


DIAGRAM 6.1.3 EXPOSURE PROFILES AT BLOCK LENGTH 15 FOR DIFFERENT SPACE SIZES AND ORIENTATIONS
(HORIZONTAL PROFILES)

in exposure values and the extent of the profile peak of space 1.

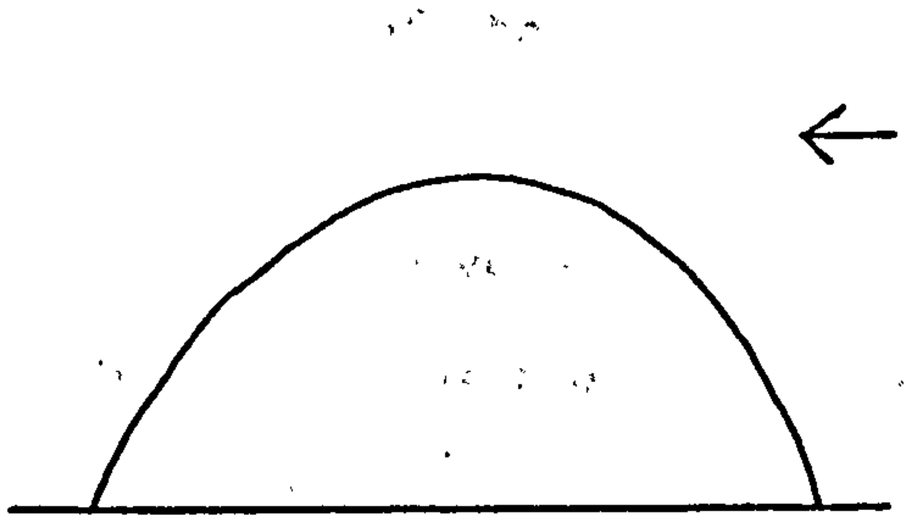
PROFILE TYPES

6.01 It can be seen from the previous sections that the exposure profile is to a large extent a characterising attribute of the air flow conditions of a given form. It can, therefore, be used in a design situation to differentiate between and/or evaluate forms, or for establishing the wind flow attributes of a given form. It might be useful for designers to have a morphology of exposure profiles pertaining to a set of linked forms. Such a morphology could help the designer, at a glance, to formulate a mental picture of the exposure changes in the vicinity of the space concerned. When such a morphology is associated with a uniform progression of forms, a great facility is provided for comparative studies.

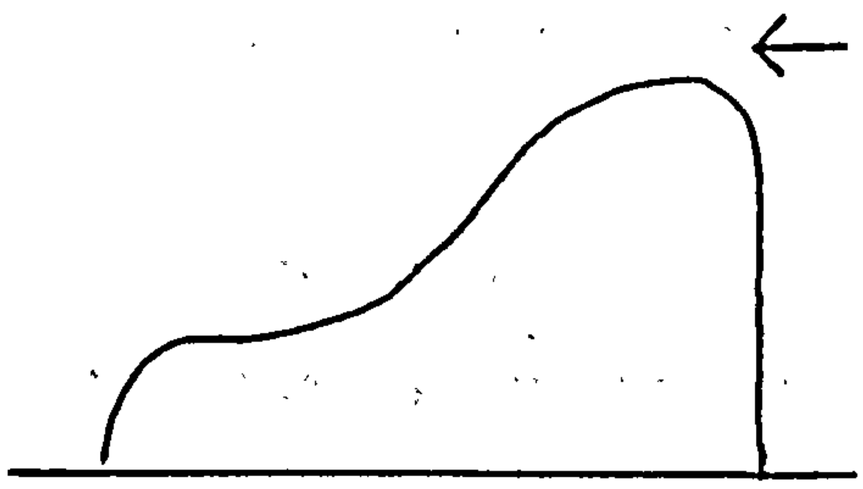
6.02 One main problem, hwoever, in the establishment of a morphology is the size of information and profile-form cases which have to be cited for even the simplest arrangements. Therefore, concise yet discerning summaries are necessary to present the information in a practical size. Such summaries can ignore the variations in actual exposure values if the profiles are topologically equivalent. They can also ignore small shifts in position within the space. An example of a profile morphology is given in the table below for the range of forms investigated.

PROFILE MORPHOLOGY

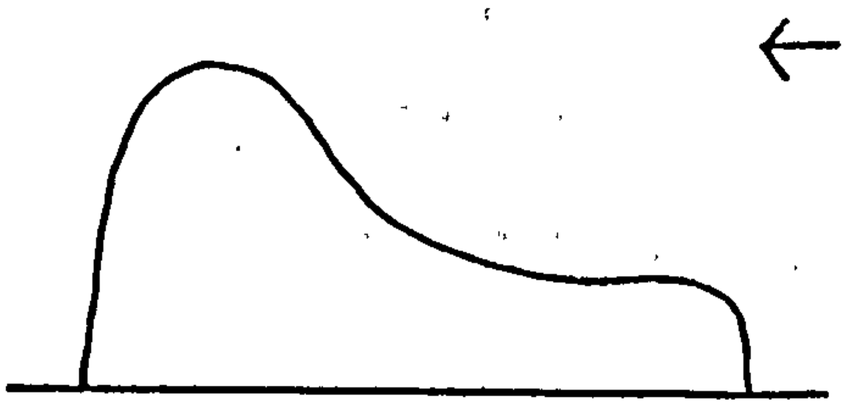
(The arrows show direction of wind flow)



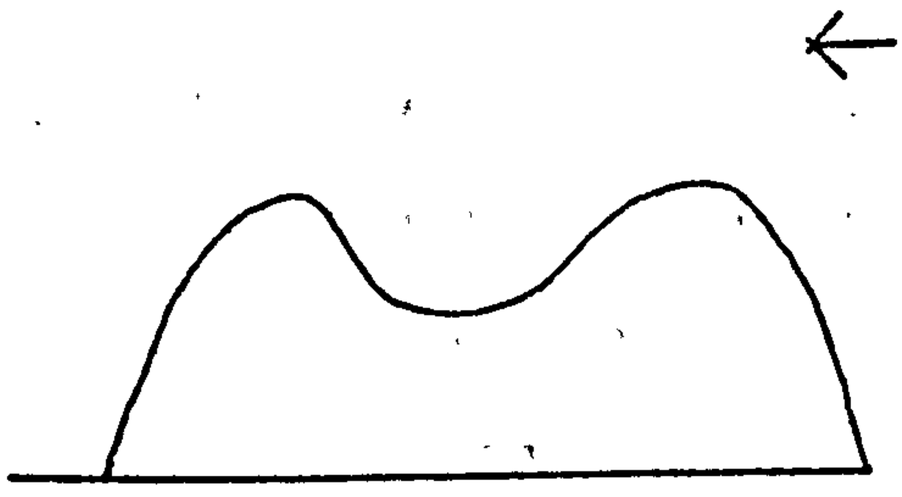
Symmetrical profile with maximum exposure values at the centre of the space; occurring at small space sizes at normal or slightly oblique orientations.



Upwind skewed profile with maximum exposure values at the upwind side of the space occurring at larger spaces, smaller block lengths for all orientations or at larger spaces, larger block lengths for oblique orientations.



Downwind skewed profile with maximum exposure values at the downwind side of the space; occurring at larger spaces of longer blocks at all orientations.



Two-peaked profile at intermediate lengths for larger spaces at all orientations but most common for the slightly oblique orientations.

ZONAL DRIFT OF THE HIGHEST EXPOSURE VALUES

7.01 One of the most revealing exposure attributes in relation to a form is the position of its highest value relative to the form. In the study of a given range of form aspects, it is informative to observe what happens to the position of such exposure values. In this section the movement of the highest exposure value from one position to another, termed the zonal drift, is studies in relation to changes in space sizes, block length and orientation. This information is derived from the exposure profiles, but presented separately for convenience and readibility.

7.02 Diagrams 6.14 - 6.19 show a graphic representation of the movement of the highest exposure values. The squares show three topological axes depicting characteristic positions in the spaces considered independent of the space size. These axes are U_z for the upwind zone, C_a for the central axis and D_z for the downwind zone. The arrow represents the movement of the highest exposure values within the space, i.e., between U_z and D_z across/from C_a. The tail of the arrow is the position of the highest exposure zone at the smallest space size, 1. Its head is the final position of the highest exposure value at the largest space, 10. Thus, the arrow in combination with the topological axes depict the continuous movement of the highest exposure as the space increases for a given block length and orientation. The patterns of movement for the 20 block lengths is represented by block length 1 - 10, 15. For each block length the movements are shown for three orientations, 0°, 30° and 45°. As an example, block length 1 at orientation 0° reads: as the space increases the position of the highest exposure value drifts from the centre of the space towards the downwind zone. At orientation 45° for block length 1, the position of the highest exposure values moves

from the central zone towards the upwind zone, but returns to the centre and continues to finish at the downwind region for the larger spaces.

7.03 At small block lengths 1, 2 and 3, and 0° orientation, the highest exposure value moves from the centre to the upwind zone before finishing at the downwind zone, except for block length 1, where the drift is direct from the centre to the downwind zone. Increasing the block length to 4 and 5 shifts the finishing position from the downwind region to the upwind region. This finishing position remain unaffected by further increase in block length. The starting position, however, is affected by increase in block length - it shifts to the downwind region for block length 7 - 10, but returns to the centre at larger block lengths.

7.04 At orientation 30° the highest exposure values show four patterns of movement. At block length 1 - 4 the highest exposure values move from the centre to the downwind region with increase in space. There is one exception to this pattern, at block length 2, where the highest exposure values show an initial drift towards the upwind region, but finish at the downwind region. The second type of drift is from the centre to the upwind region, shown by spaces 5 - 6. This si a reversal of the previous pattern, resulting from increase in block length. Increasing the block length to 7 - 10 shows a third type of movement: from the centre to the upwind region, a return to the centre, and finally finishing in the downwind region. Larger block lengths show the reverse of the previous pattern: starting at centre, drifting towards the downwind region, but ending at the upwind region.

7.05 At orientation 45°, the movement of the highest exposure value is more consistent in its finishing positions, i.e., at larger spaces, but

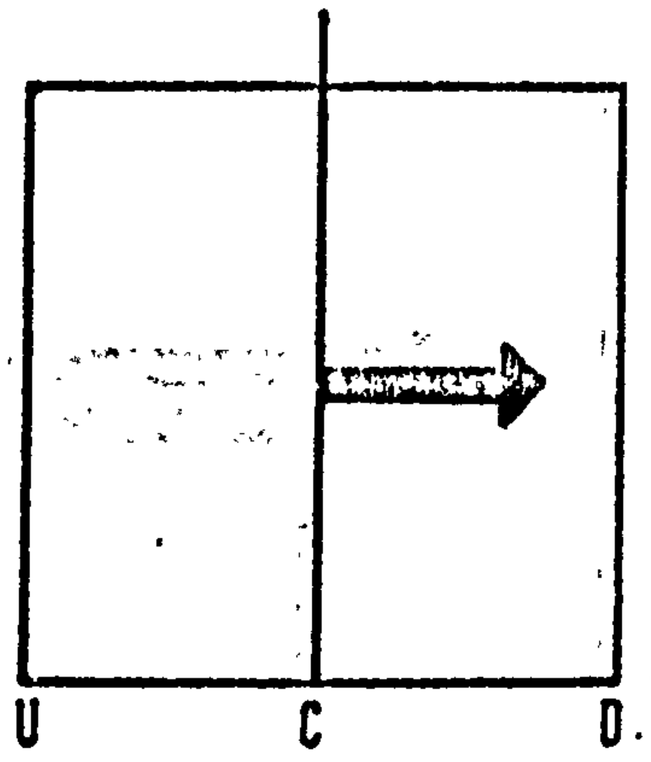
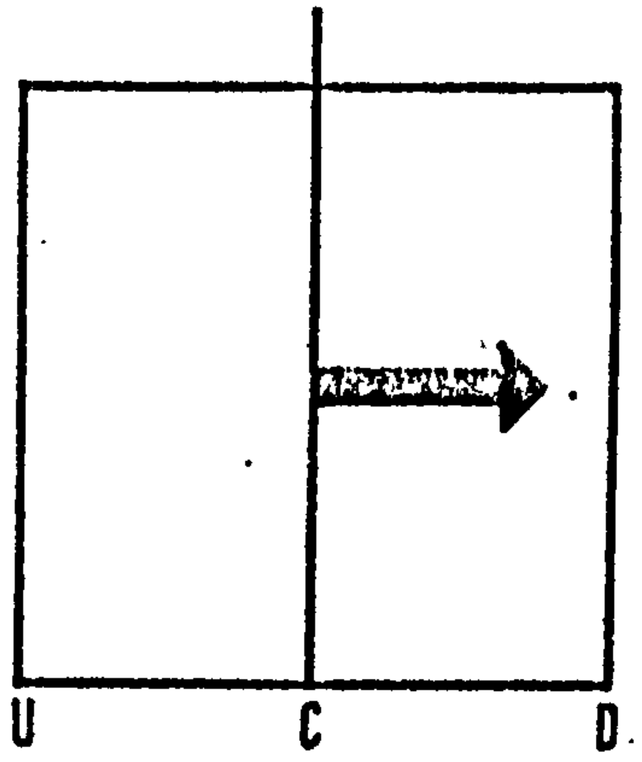
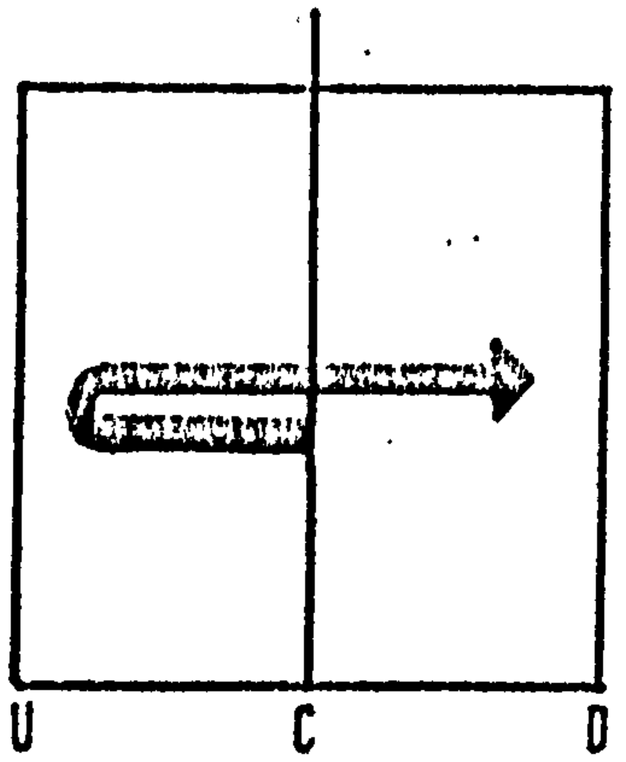
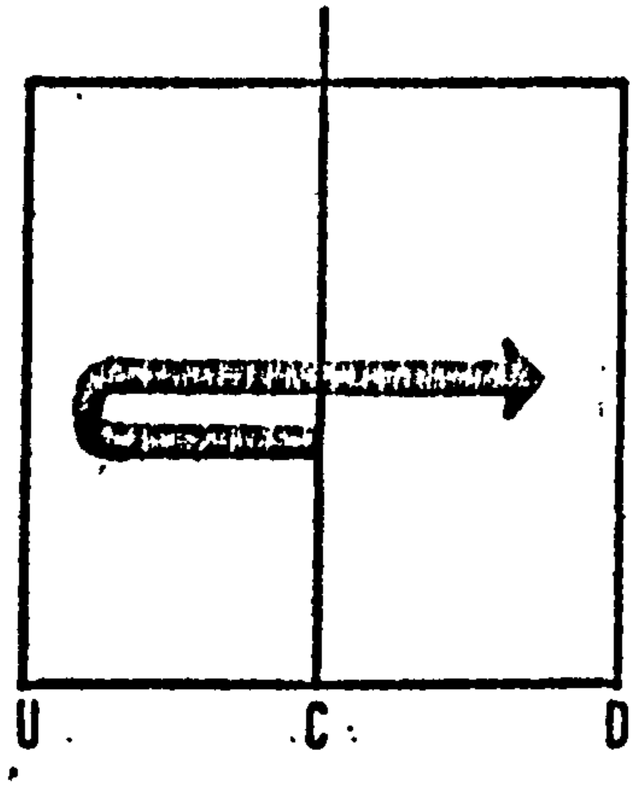
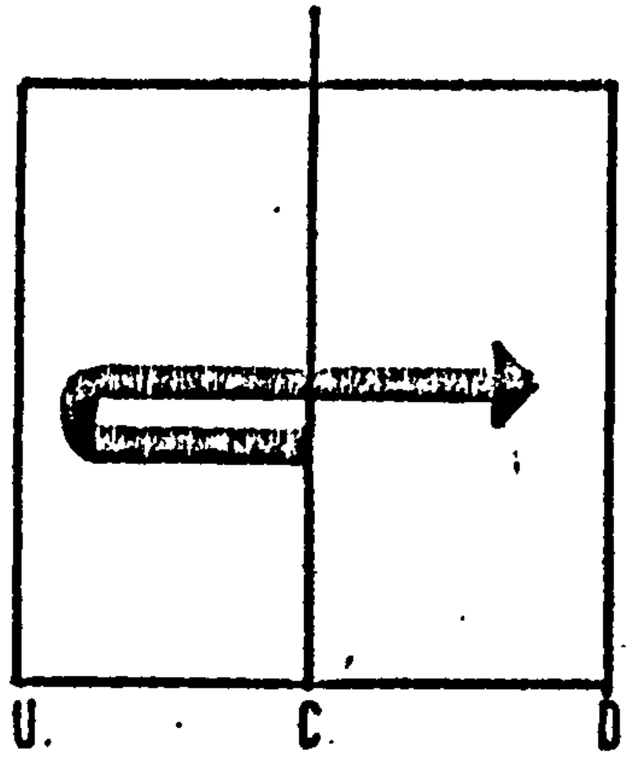
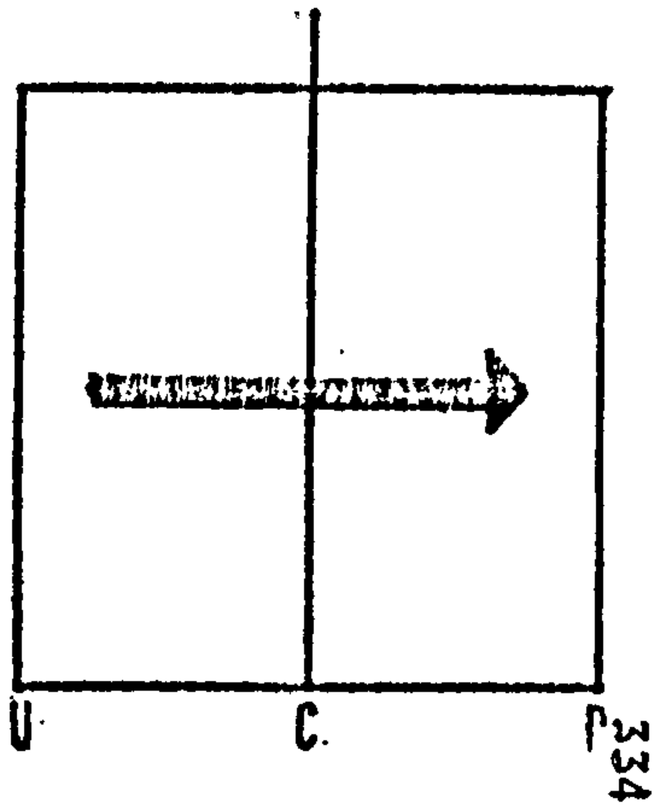
BLOCK LENGTH	MOVEMENT REPRESENTATION ORIENTATION 0	30	45
1			
2			

DIAGRAM 6.14: ZONAL DRIFT OF THE HIGHEST EXPOSURE VALUES (BLOCK LENGTHS 1 - 2)

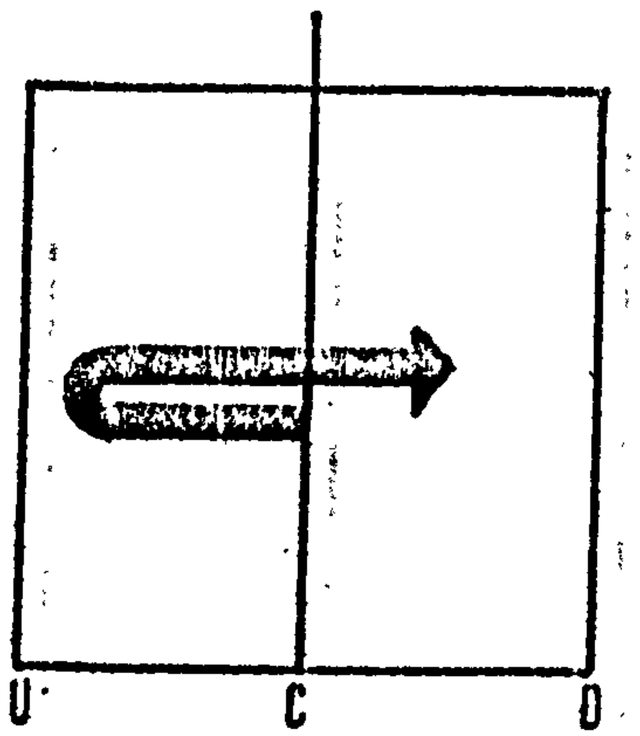
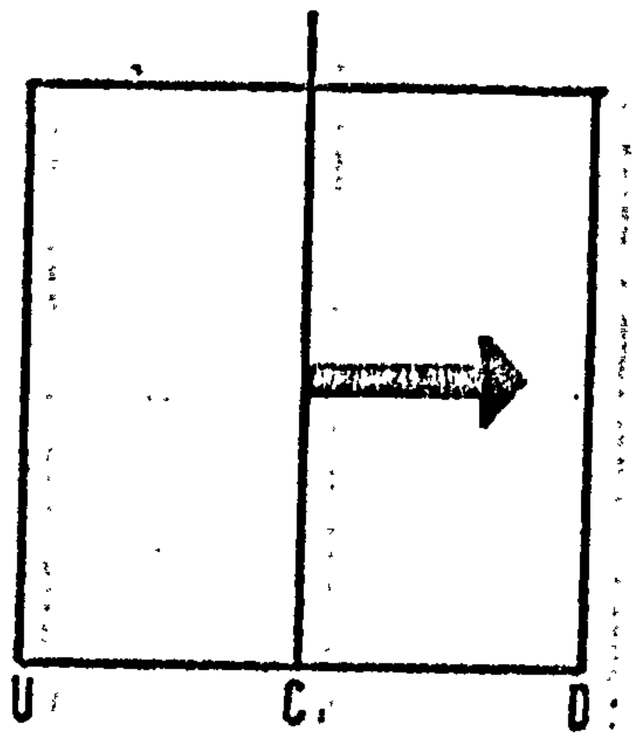
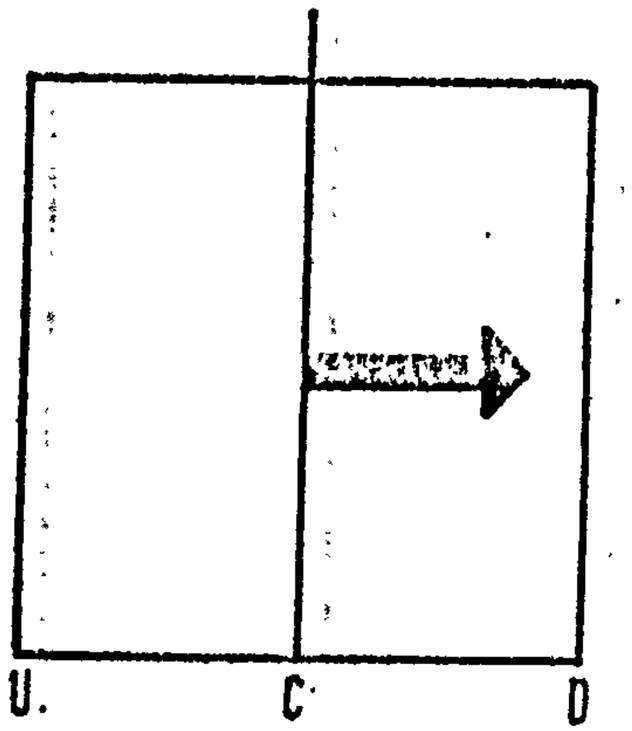
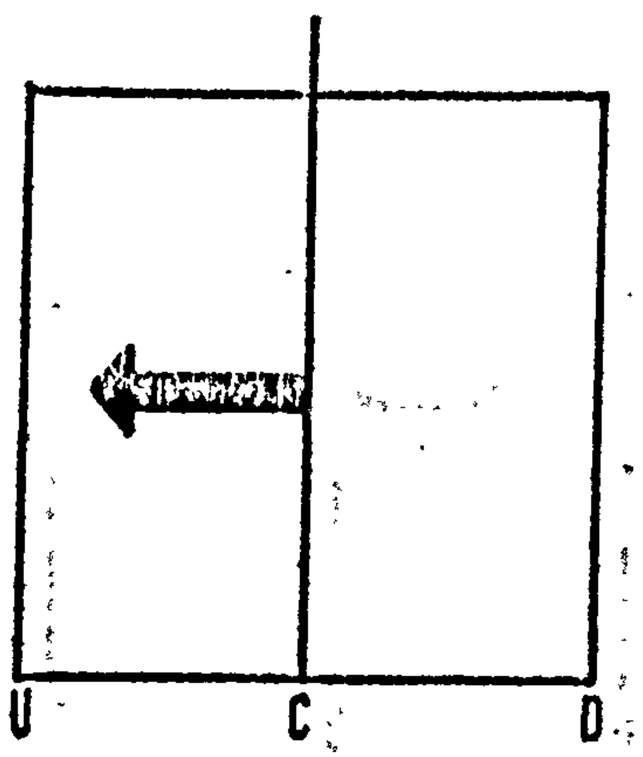
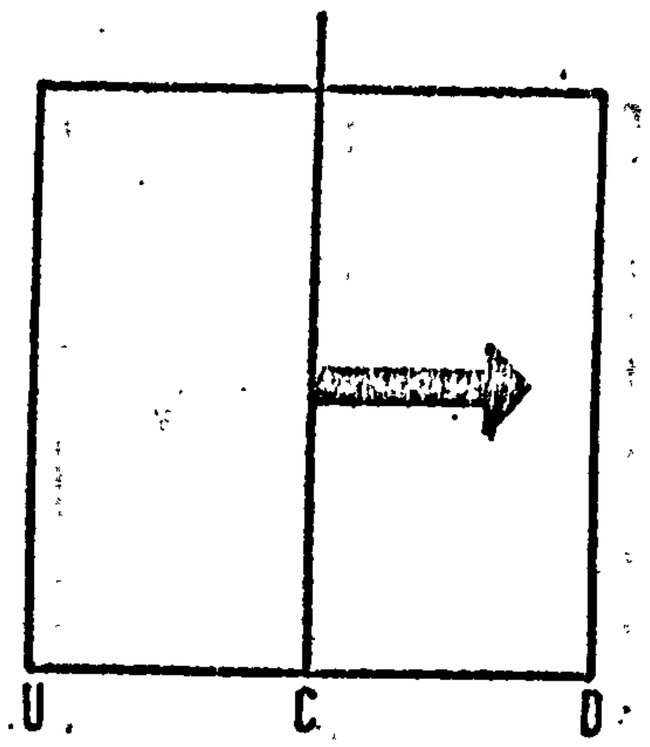
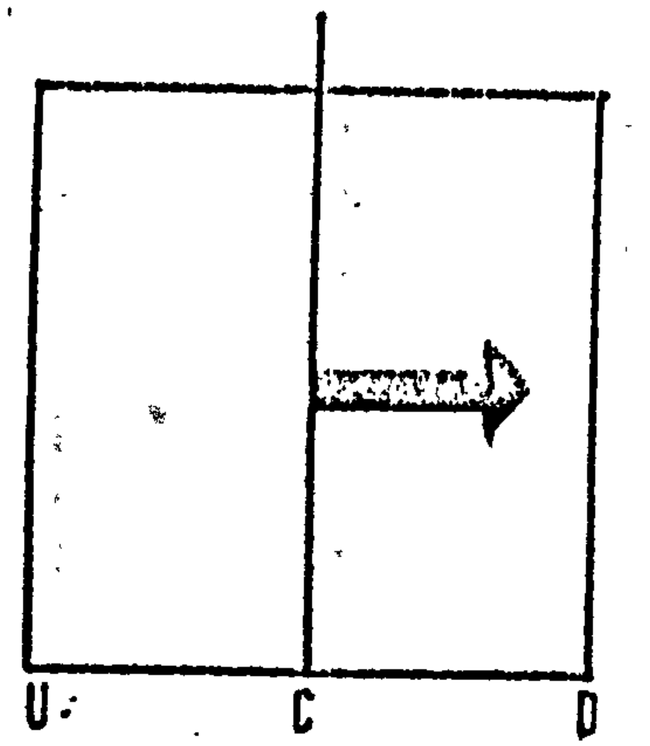
BLOCK LENGTH	MOVEMENT REPRESENTATION — ORIENTATION 0	30	45
3			
4			

DIAGRAM 6.15: ZONAL DRIFT OF THE HIGHEST EXPOSURE VALUES (BLOCK LENGTH 3 - 4)

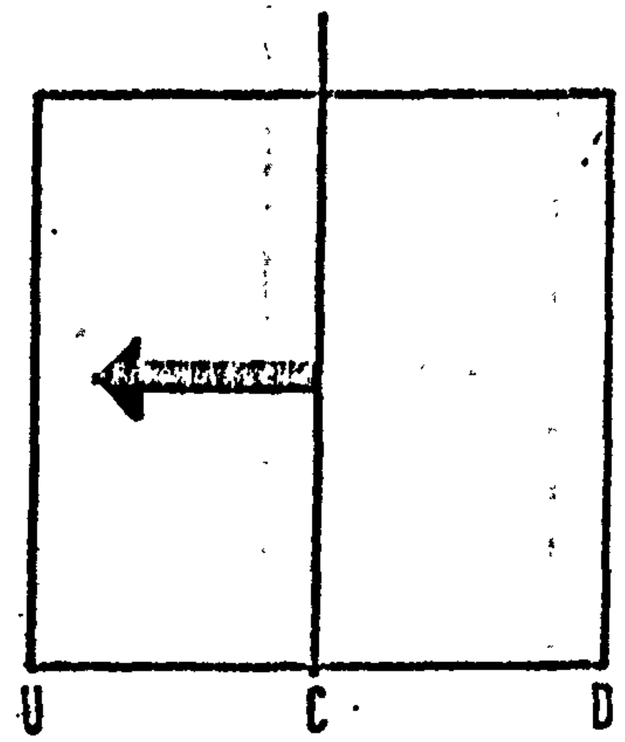
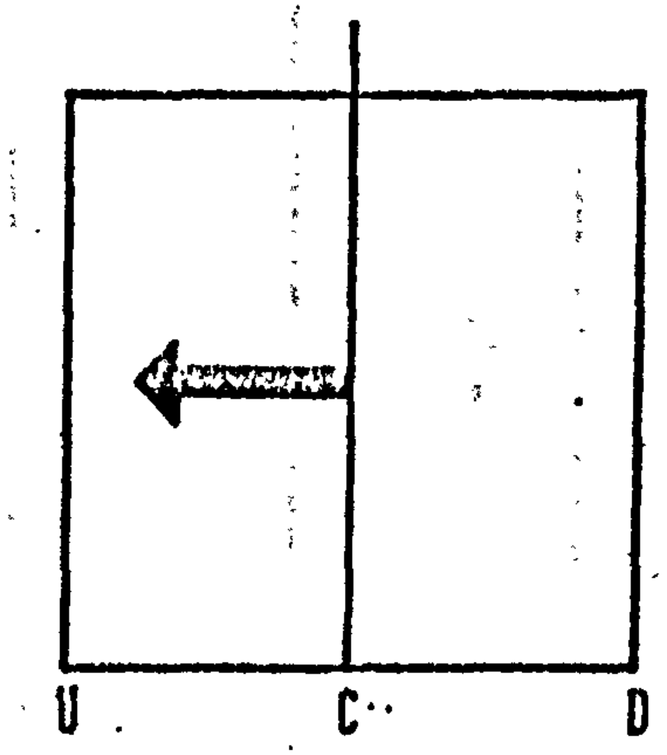
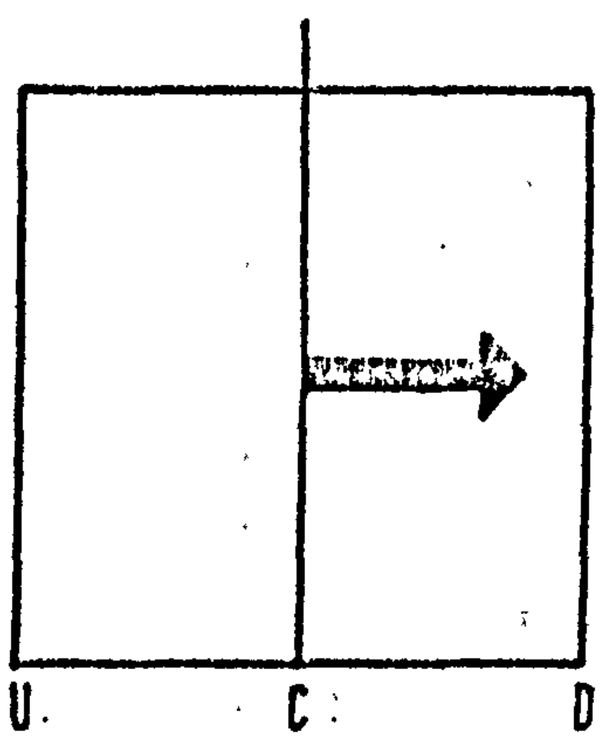
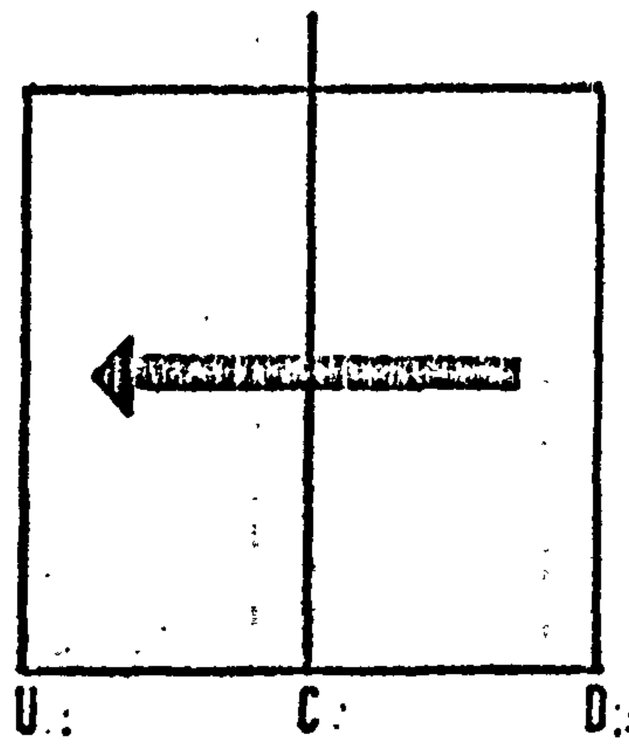
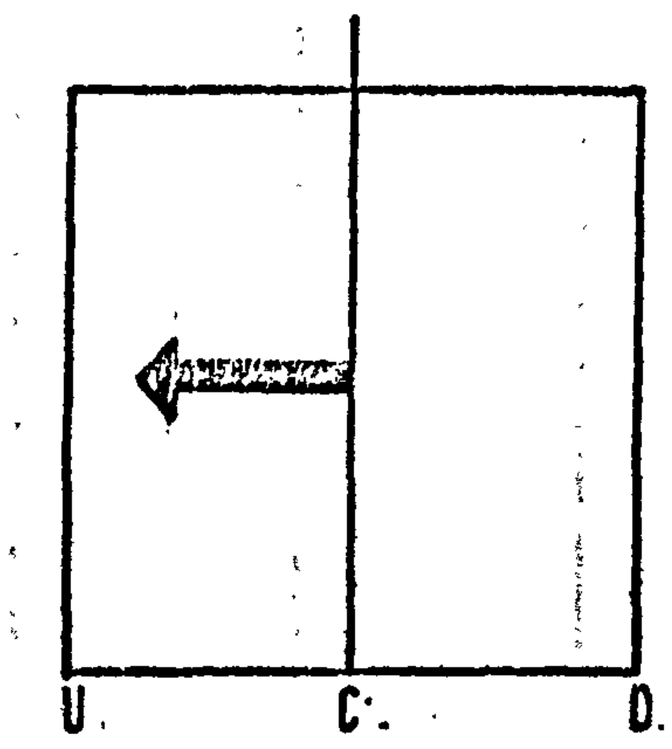
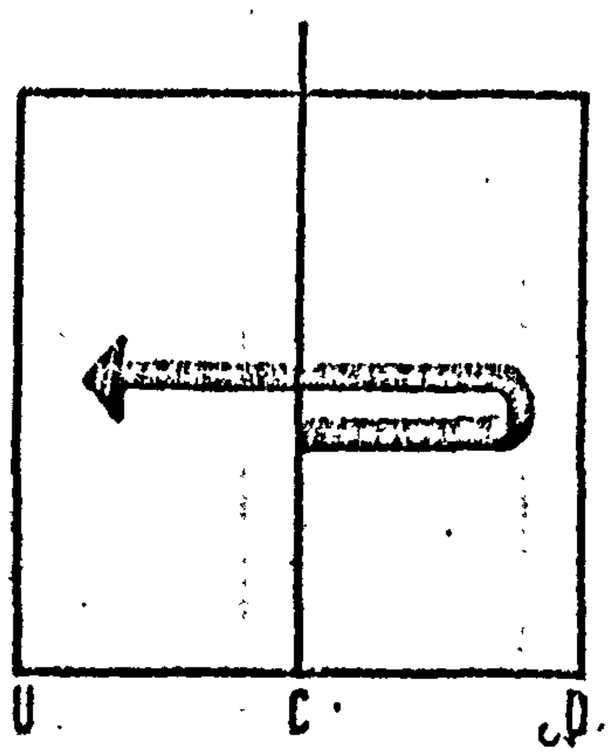
BLOCK LENGTH	MOVEMENT REPRESENTATION — ORIENTATION 0	30	45
5			
6			

DIAGRAM 6.16: ZONAL DRIFT OF THE HIGHEST EXPOSURE VALUES (BLOCK LENGTHS 5, 6)

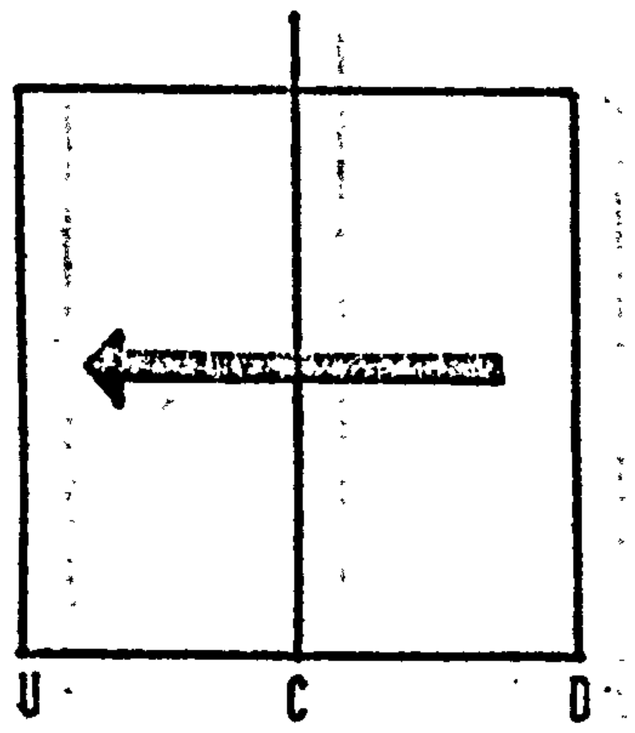
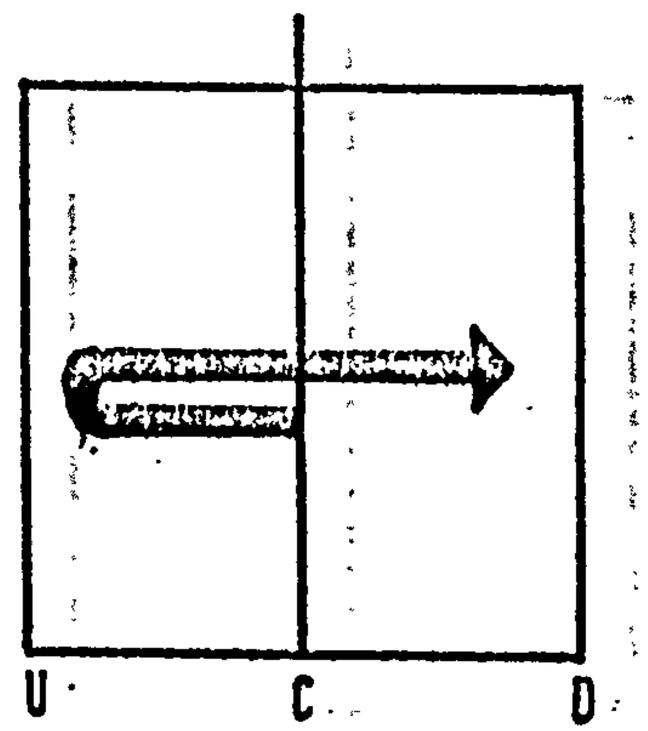
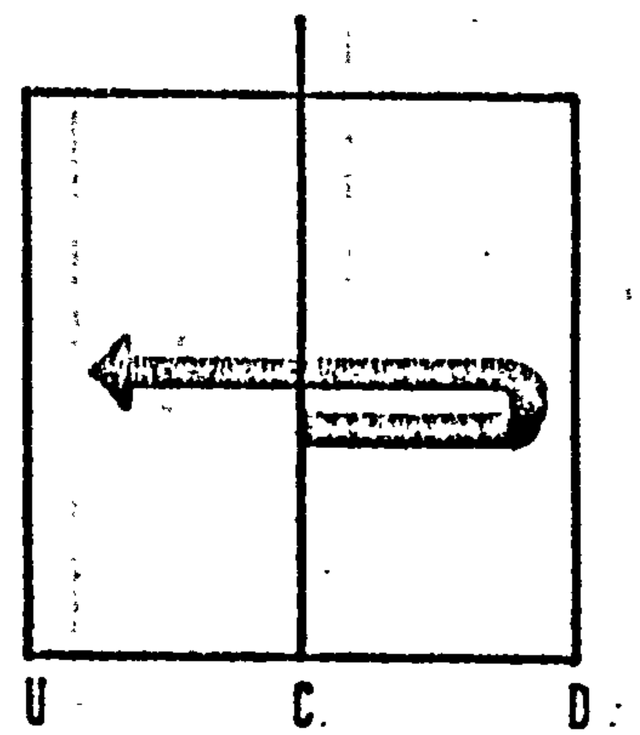
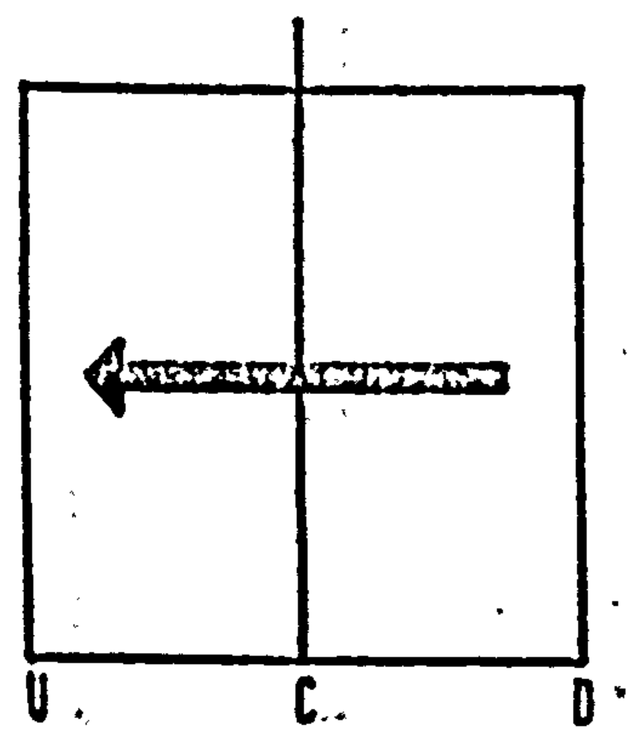
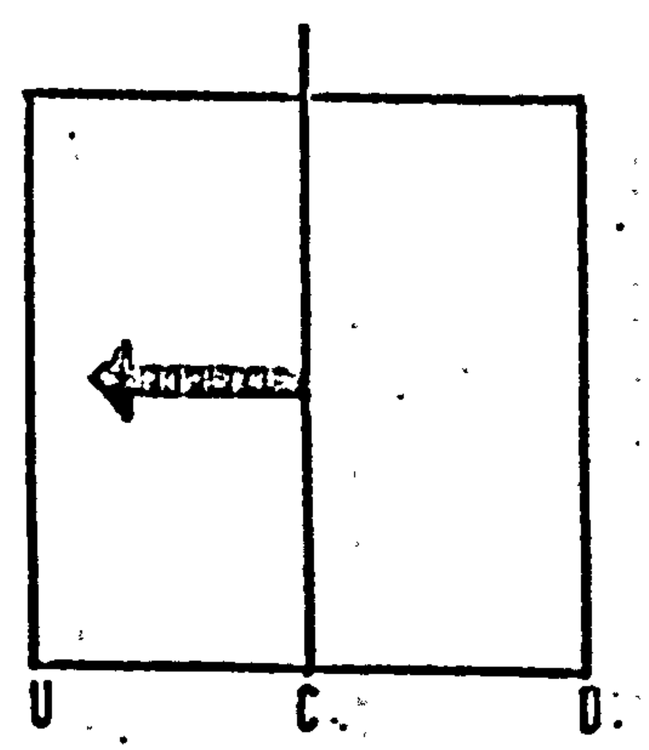
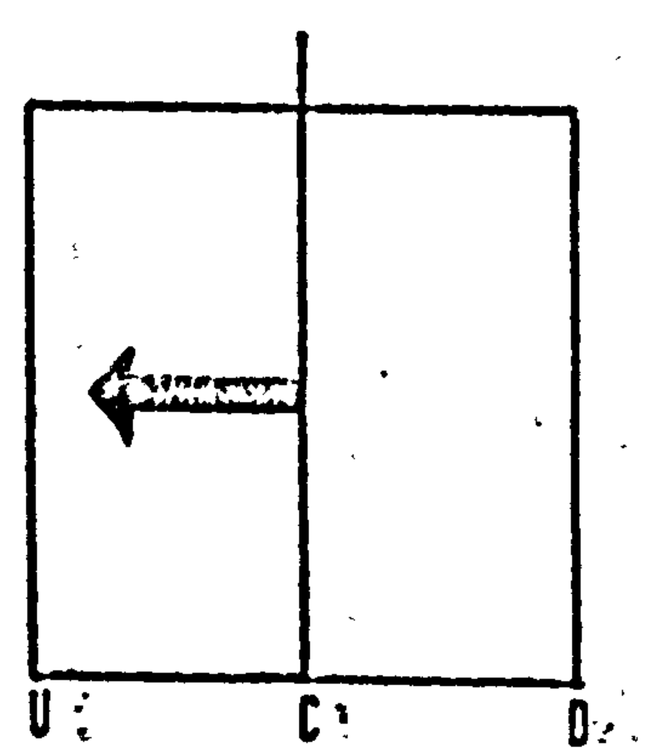
BLOCK LENGTH	MOVEMENT REPRESENTATION — ORIENTATION 0	30	45
7			
8			

DIAGRAM 6.17: ZONAL DRIFT OF THE HIGHEST EXPOSURE VALUES (BLOCK LENGTHS 7, 8)

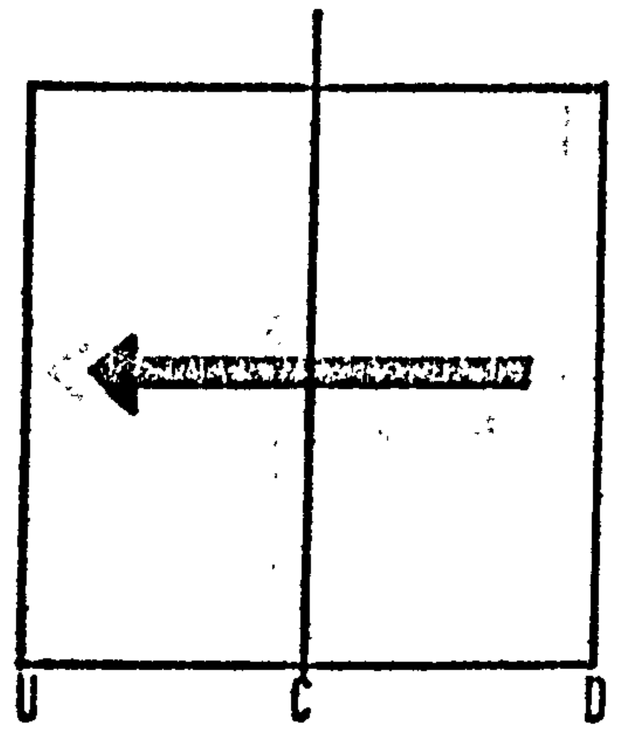
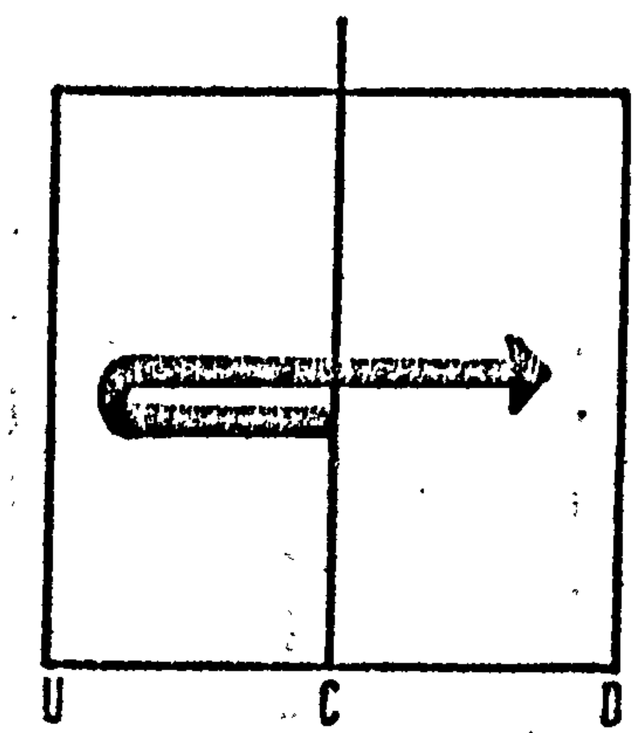
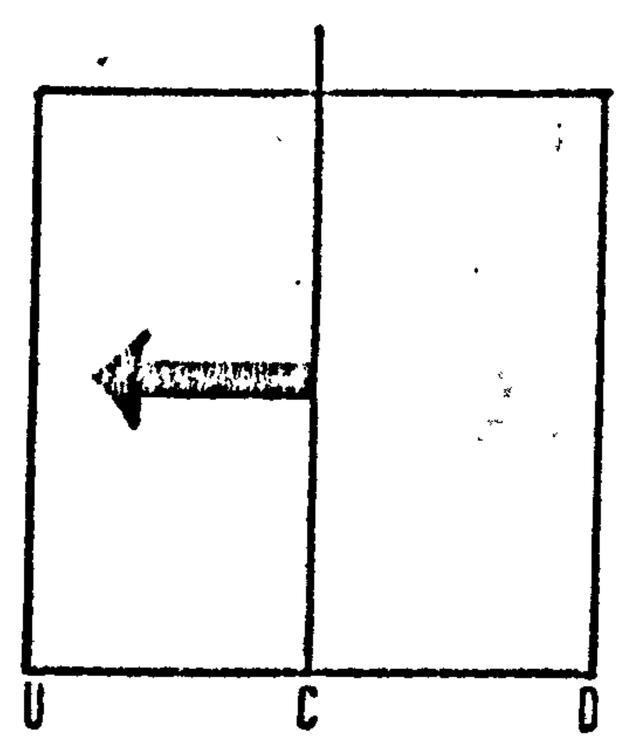
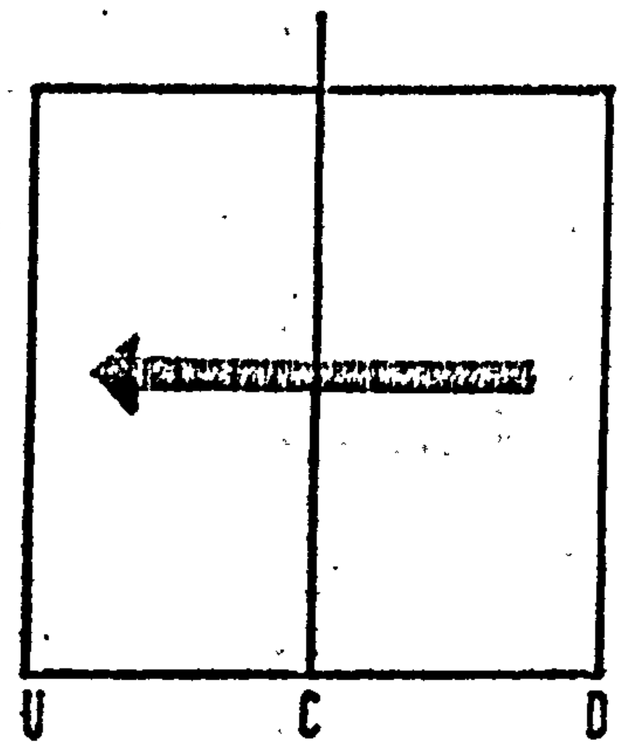
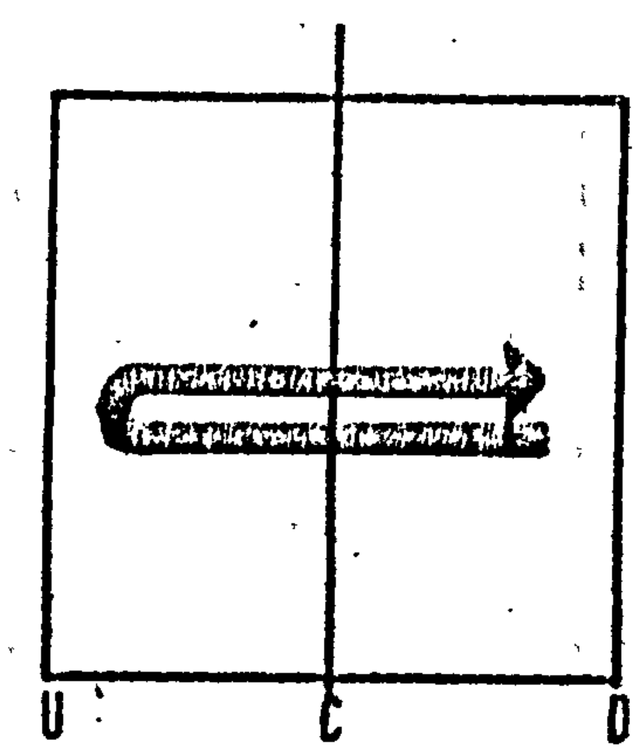
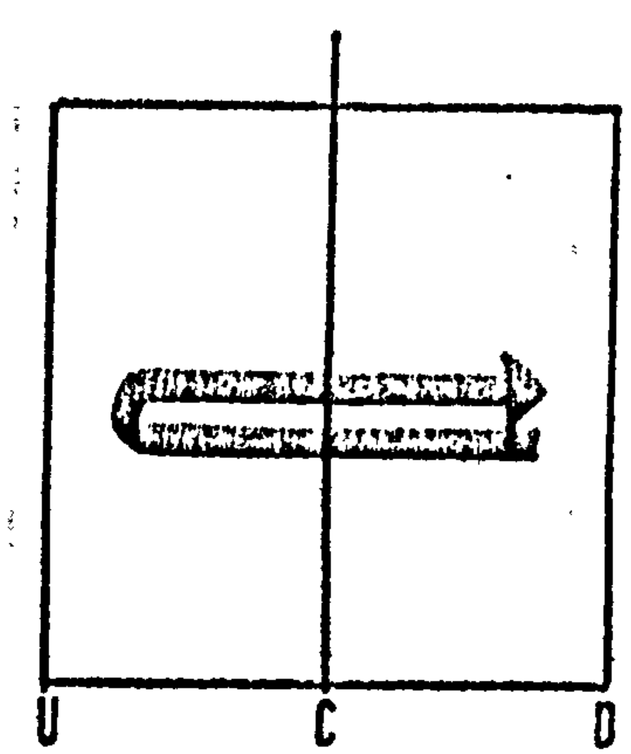
BLOCK LENGTH	MOVEMENT REPRESENTATION — ORIENTATION 0	30	45
9			
10			

DIAGRAM 6.18: ZONAL DRIFT OF THE HIGHEST EXPOSURE VALUES (BLOCK LENGTHS 9, 10)

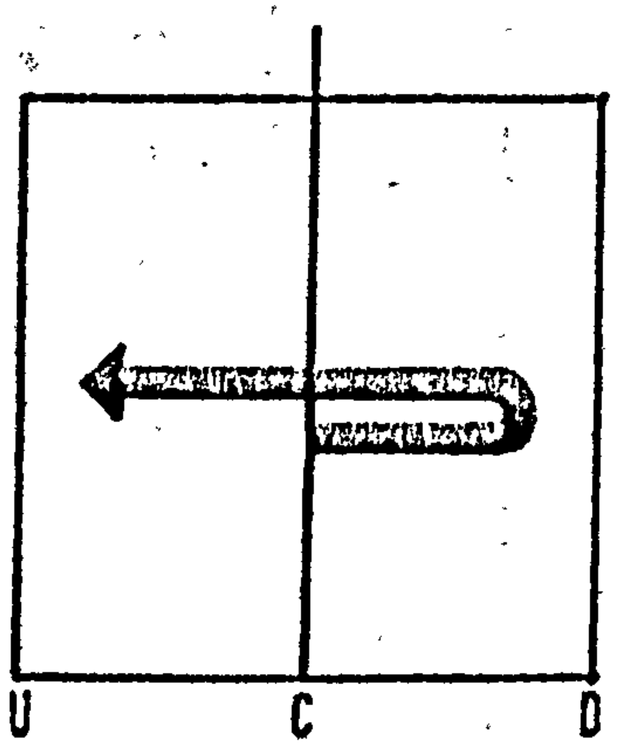
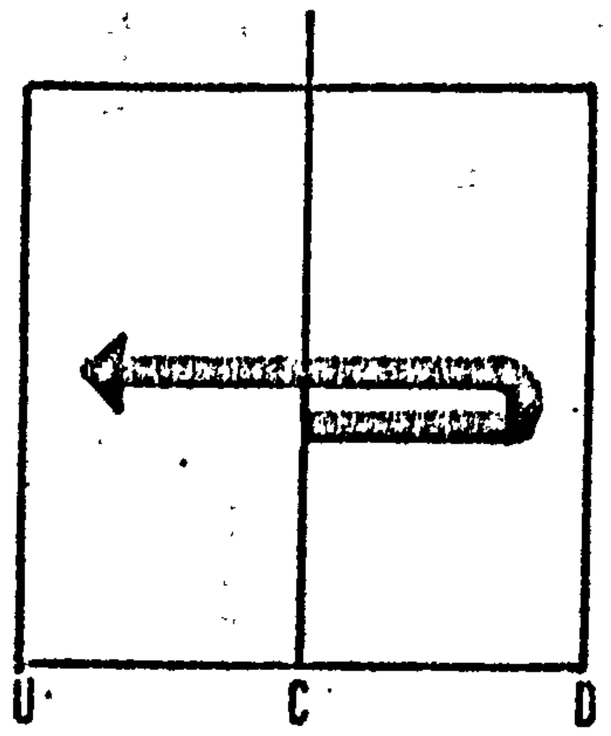
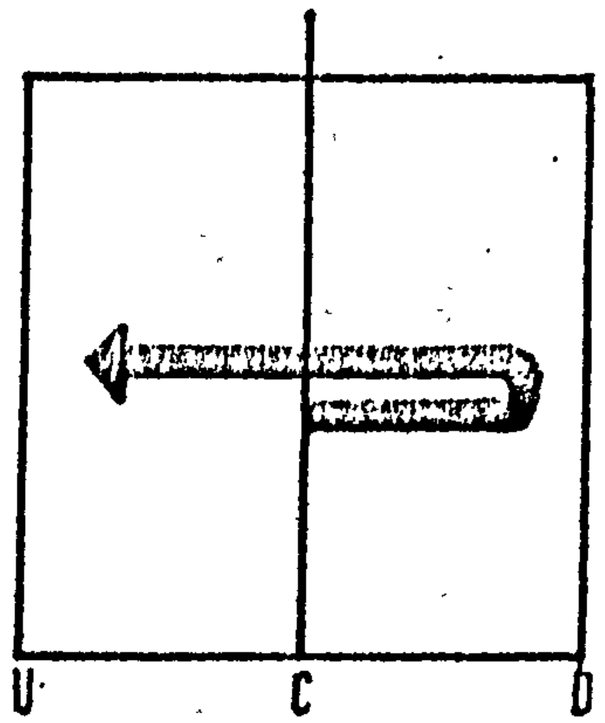
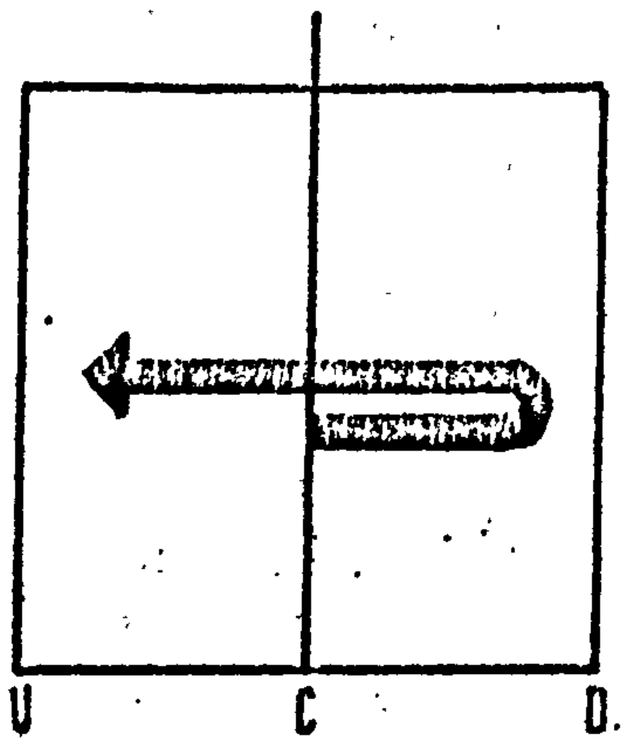
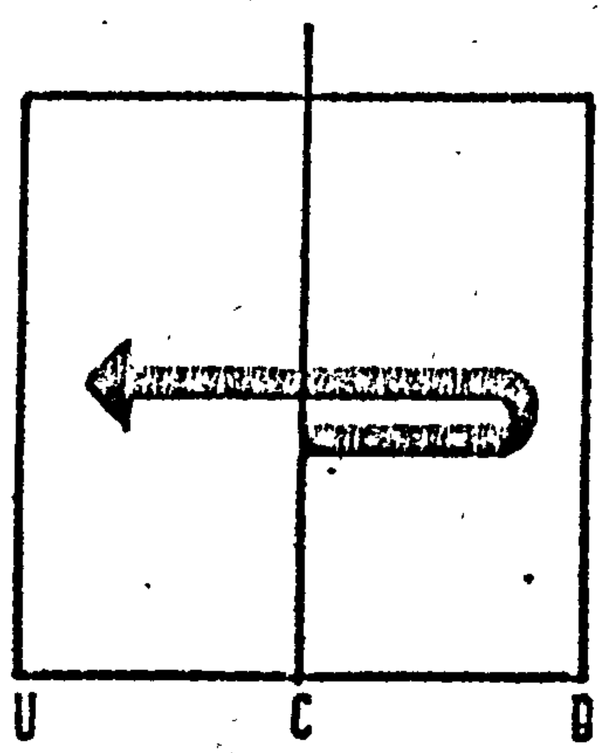
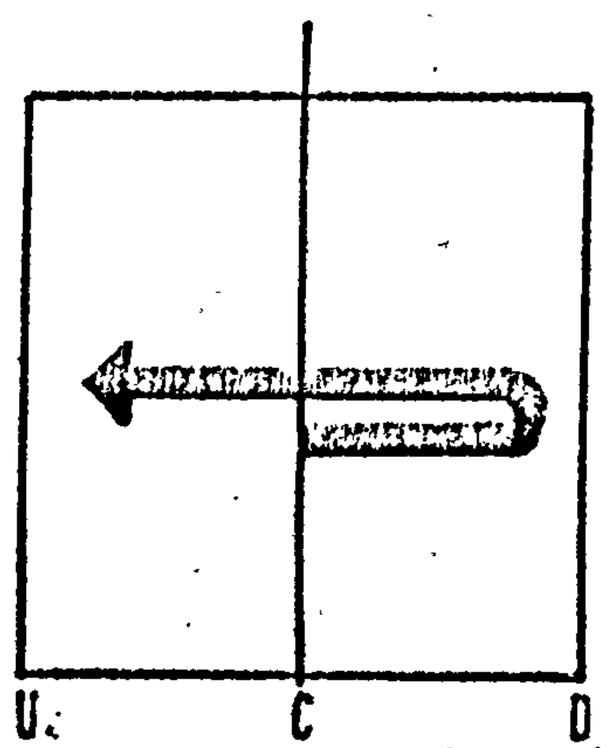
BLOCK LENGTH	MOVEMENT REPRESENTATION — ORIENTATION 0	30	45
15			
20			

DIAGRAM 6.19: ZONAL DRIFT OF THE HIGHEST EXPOSURE VALUES (BLOCK LENGTHS 15, 20)

showing less regular patterns at smaller spaces. Thus, spaces 1 - 5 show finishing positions at the downwind region, but at small spaces the highest exposure value shifts its position from centre to the upwind region.

7.06 The drift of the highest exposure value as the spaces increase in size and as the block length and orientation change show a generally uniform and consistent movement within the space. This pattern of uniform and consistent drift is, however, less obvious at smaller spaces; but it becomes more stable at larger spaces, and it correlates fairly well with the increase in block length.

THE LOCALISATION FACTOR

8.01 It can be seen from the profiles of the exposure of the different arrangements that at least one peak occurs in each profile. The peaks are different in value and extent within the space represented by the profile. It is proposed here that the value and extent of the peaks are closely linked with the form aspects considered, i.e., block length, space size, and orientation; and that the peaks values and their spatial extent can be represented by a numerical scale.

8.02 In this section a numerical index is developed to describe the profile by taking the value and extent of its peak. This index will be termed the localisation factor. The nearest measure to the idea of the localisation factor is the statistical measure of Kurtosis, which describes the departure of a given distribution curve from the normal, i.e., a measure of skewness. If applied to describe the exposure profile, it is likely to be unsuitable on two counts. First, it is

more beneficial to have unique descriptors of profiles by assigning them absolute numerical values, but not values relative to a reference profile. Second, the spatial extent of the peak value will be sacrificed which means that a unique aspect of the profile is left out.

8.03 After trying a number of formulations combining the peak value and its extent, it was found that the following formulation correlates well with the changes in the form aspects, and the subsequent changes in their profiles:

$$F = \frac{I_{max}\,(I_{max} - I_{min})}{N_z}$$

where F is the Localisation Factor.

I_{max} is the peak value of the exposure in the relevant profile (an average in a range of 5%).

I_{min} is the minimum value of the exposure in the relevant profile.

N_z is the number of zones in the profile to which I_{max} extends.

8.04 An initial formulation of the localisation factor was to take the maximum exposure value of the profile. This did not provide a sufficient differentiation of form-profile relationships, since different arrangements would show the same localisation factor values although they have different profiles. Another formulation which incorporates the spatial extent in:

$$\frac{I_{max}}{N_z}$$

was only slightly better than the first but was rather insensitive to changes in profile shapes and, therefore, unsuitable for differentiation between the different forms. All these defects shown in the two formulations are avoided in F by introducing the range of the profile

$(I_{max} - I_{min})$, as a multiplication factor by the profile peak value I_{max}.

8.05 The space is divided into 10 zones and N_z can take values between 1 and 10. F takes values greater than zero and less than one. The nearer the values of F to the upper limit, 1, the greater the localisation of the exposure, i.e., high exposure values concentrated in relatively small portions of the space.

8.06 Diagram 6.20 shows the relationship between the localisation factor F and space size for different block lengths at orientation 0°. It shows higher values of the localisation factor for shorter block lengths at larger spaces, and lower at space 1. The values of F are closest for all block lengths at space 2. The range of values that F takes increases with increase in space, but the lowest values occur at the shortest block length.

8.07 Diagrams 6.21 - 6.28 show the relationship between the localisation factor and space size for different orientations of block lengths 1, 2, 4, 6, 8, 10, 15 and 20. For the shorter block lengths the values of F increase relatively sharply with the increase in space size. The values of F are higher at orientation 0° and lowest at orientation 45° at block length 1. This situation is reversed for block lengths 2 and 4, but it returns at longer block lengths at larger space sizes. The range of values of F decreases with increase in block length for the given range of space sizes and becomes very close at block lengths 15 - 20.

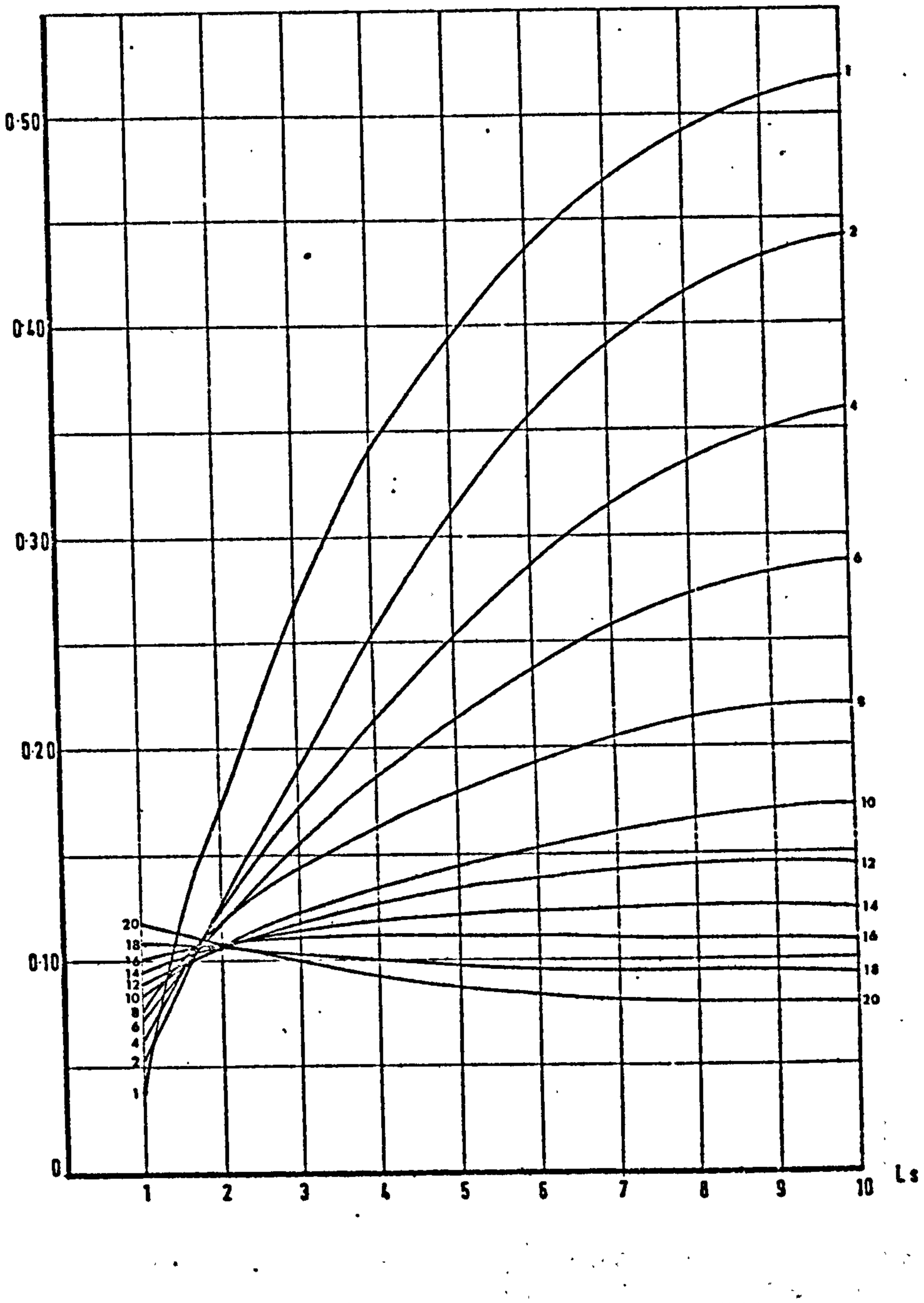


DIAGRAM 6.20: RELATIONSHIP BETWEEN LOCALISATION FACTOR, F, AND SPACE SIZE (L_s) FOR DIFFERENT BLOCK LENGTHS (1 to 20) AT ORIENTATION 0°

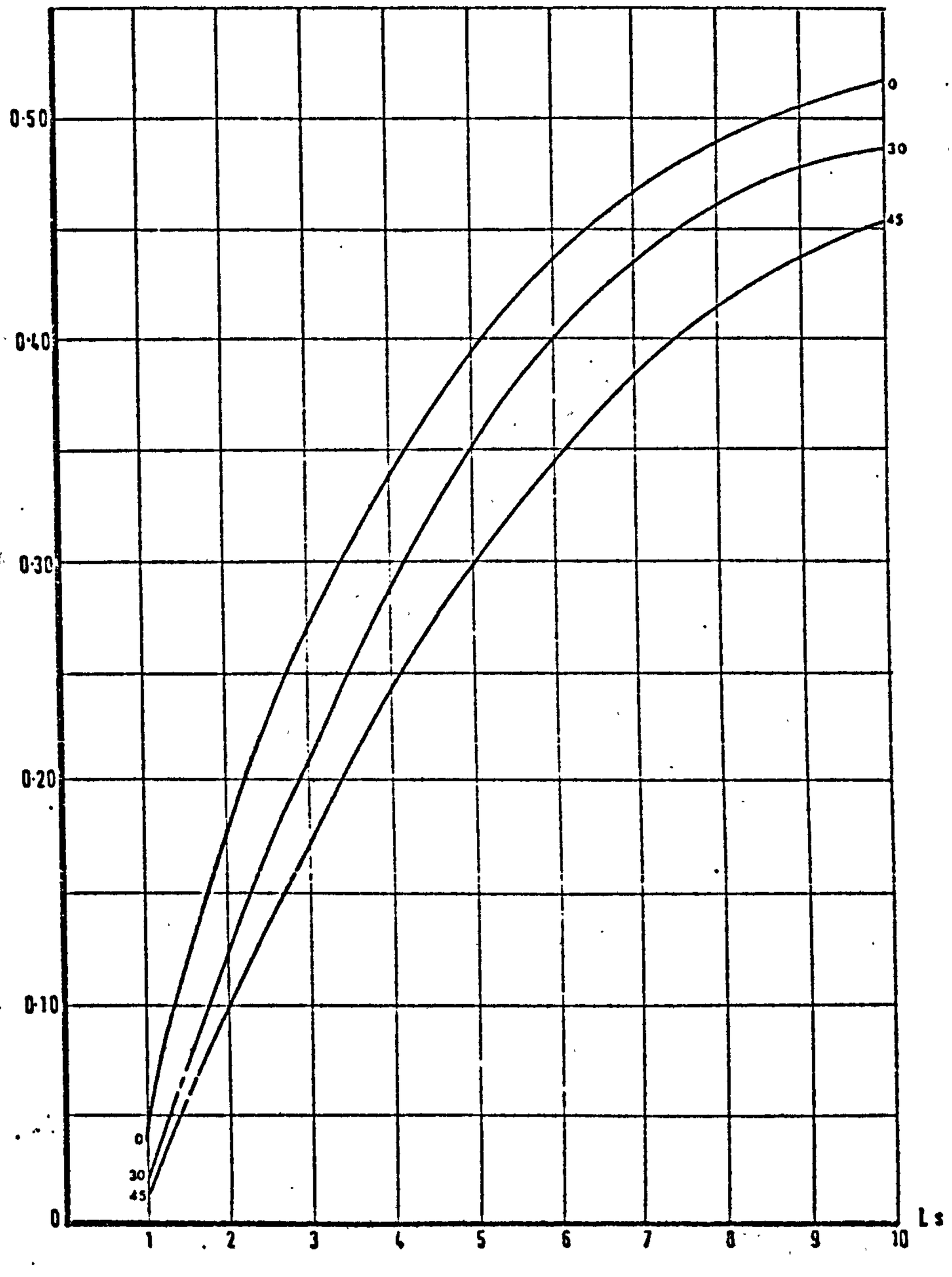


DIAGRAM 6.21: RELATIONSHIP BETWEEN THE LOCALISATION FACTOR, F, AND SPACE SIZE AT DIFFERENT ORIENTATIONS FOR BLOCK LENGTH 1.

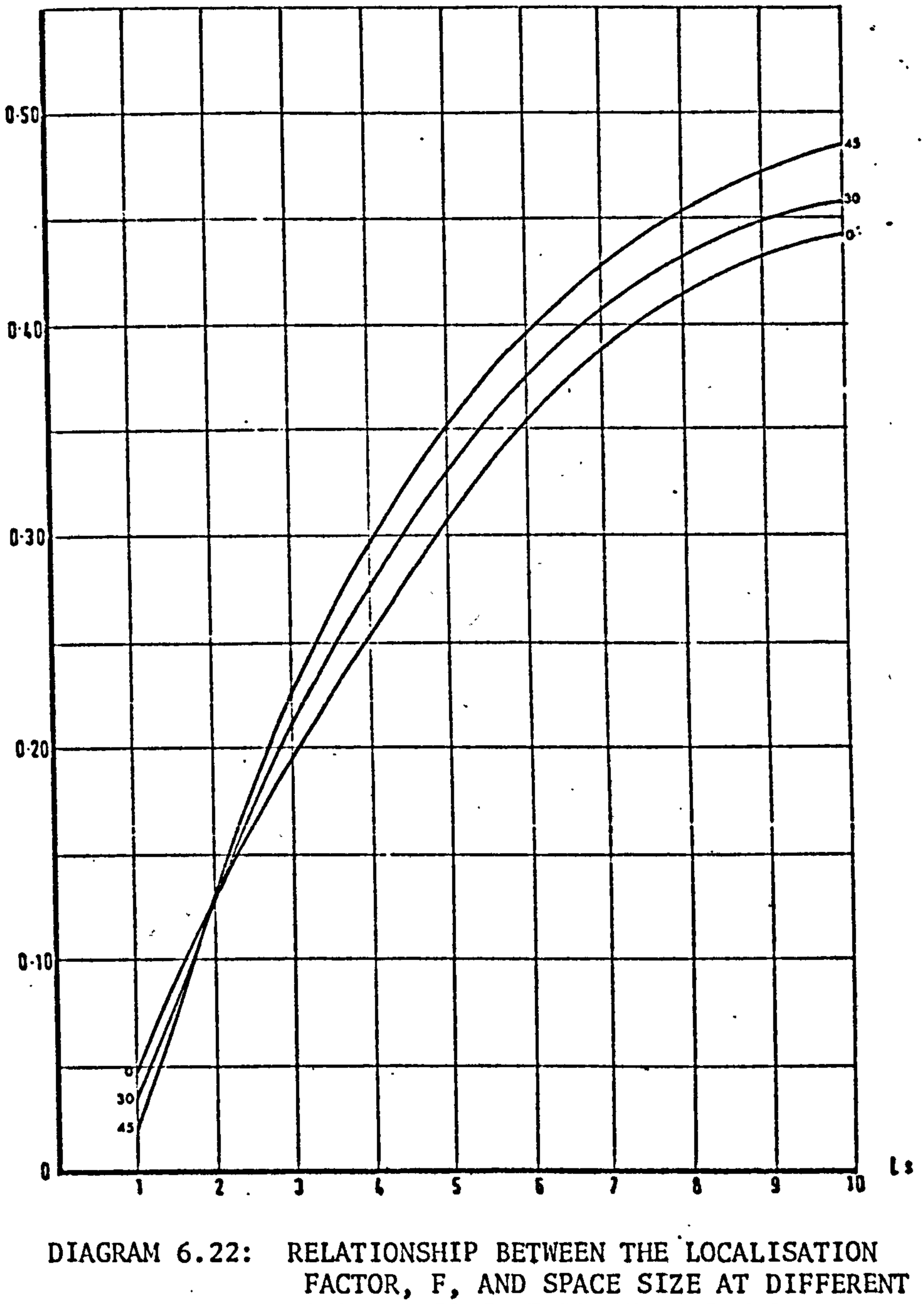


DIAGRAM 6.22: RELATIONSHIP BETWEEN THE LOCALISATION FACTOR, F, AND SPACE SIZE AT DIFFERENT ORIENTATIONS OF BLOCK LENGTH 2.

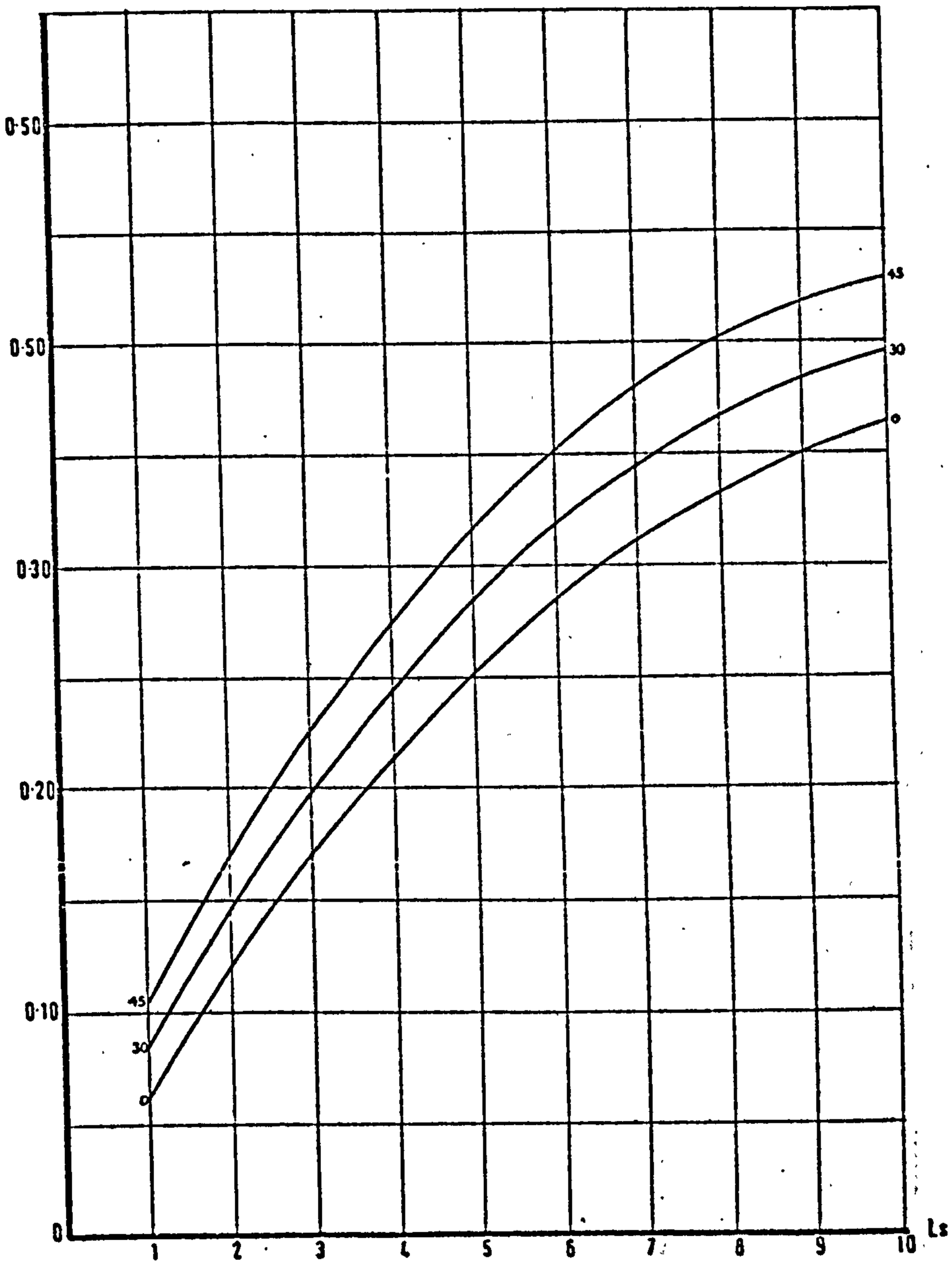


DIAGRAM 6.23: RELATIONSHIP BETWEEN THE LOCALISATION FACTOR, F, AND SPACE SIZE AT DIFFERENT ORIENTATIONS OF BLOCK LENGTH 4.

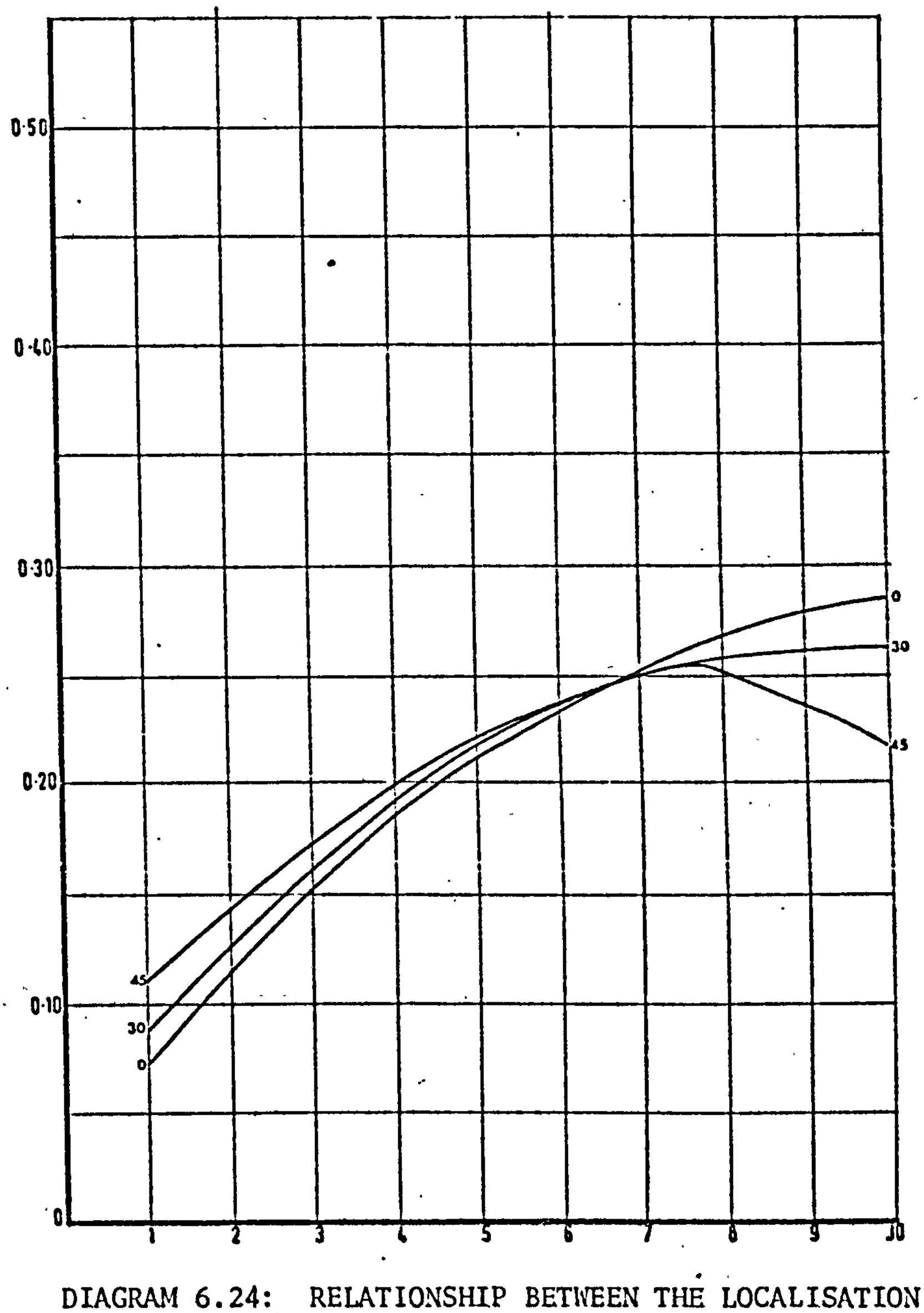


DIAGRAM 6.24: RELATIONSHIP BETWEEN THE LOCALISATION FACTOR, F, AND SPACE SIZE AT DIFFERENT ORIENTATIONS OF BLOCK LENGTH 6.

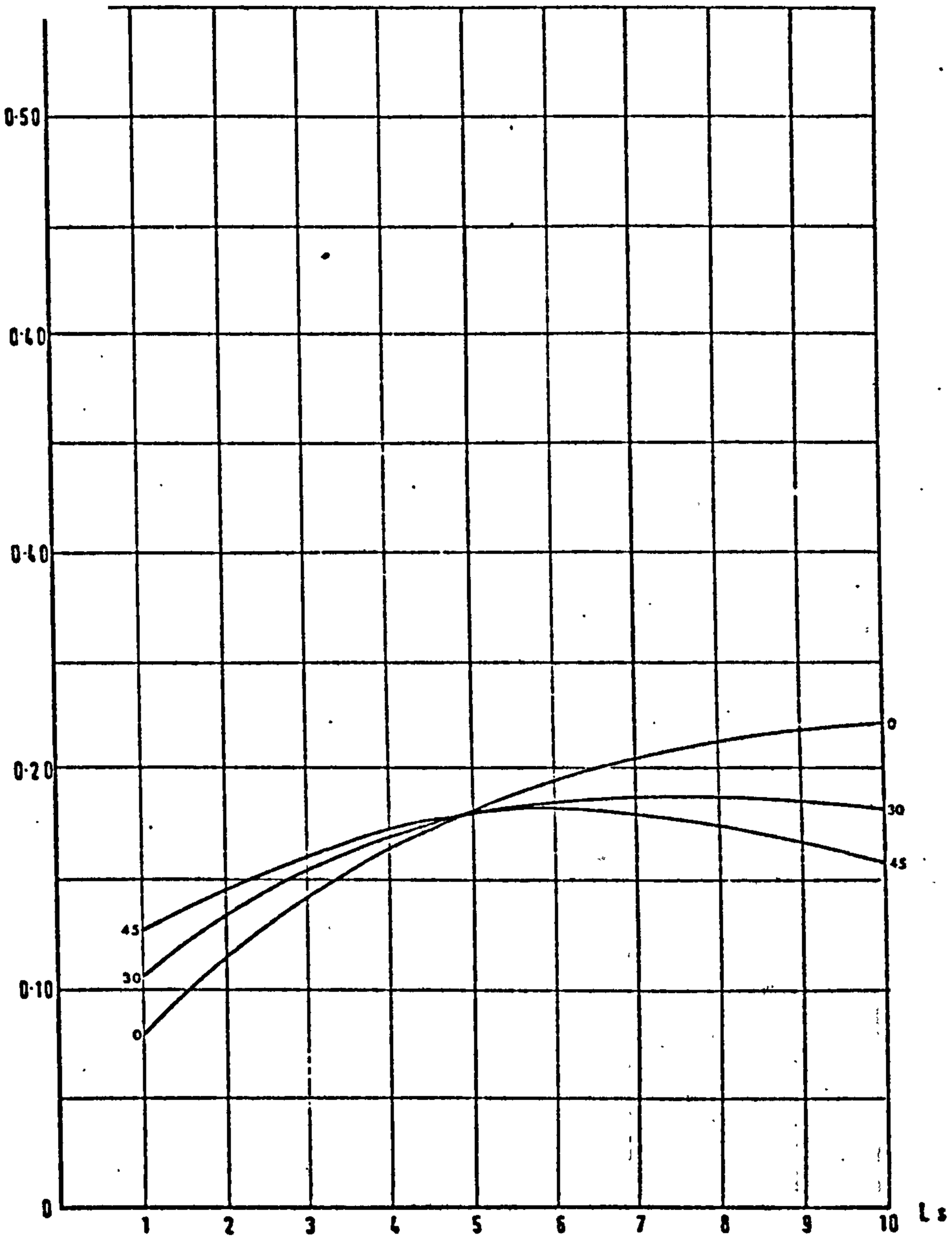


DIAGRAM 6.25: RELATIONSHIP BETWEEN THE LOCALISATION FACTOR, F, AND SPACE SIZE AT DIFFERENT ORIENTATIONS OF BLOCK LENGTH 8.

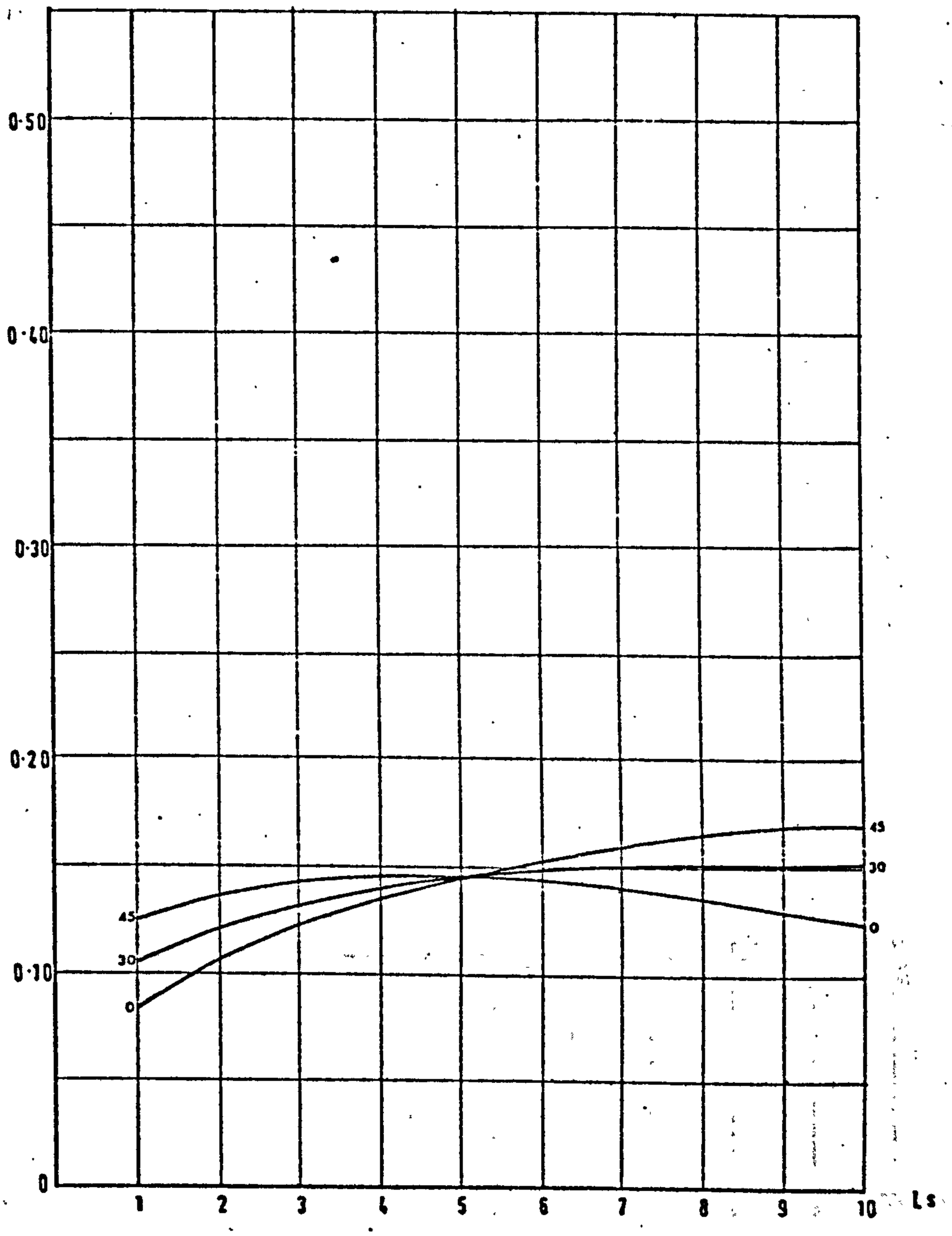


DIAGRAM 6.26: RELATIONSHIP BETWEEN THE LOCALISATION FACTOR, F, AND SPACE SIZE AT DIFFERENT ORIENTATIONS OF BLOCK LENGTH 10.

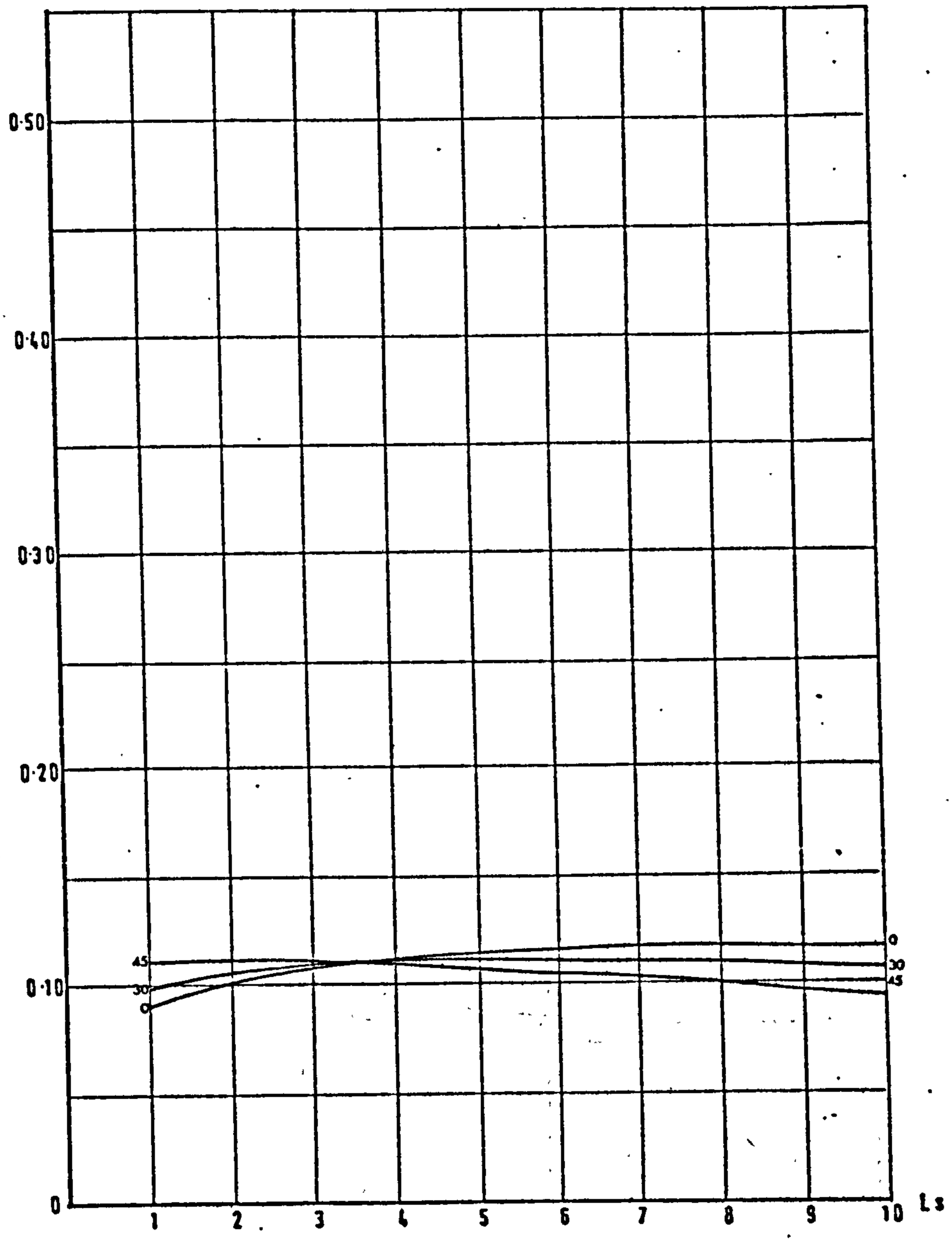


DIAGRAM 6.27: RELATIONSHIP BETWEEN THE LOCALISATION FACTOR, F, AND SPACE SIZE AT DIFFERENT ORIENTATIONS OF BLOCK LENGTH 15.

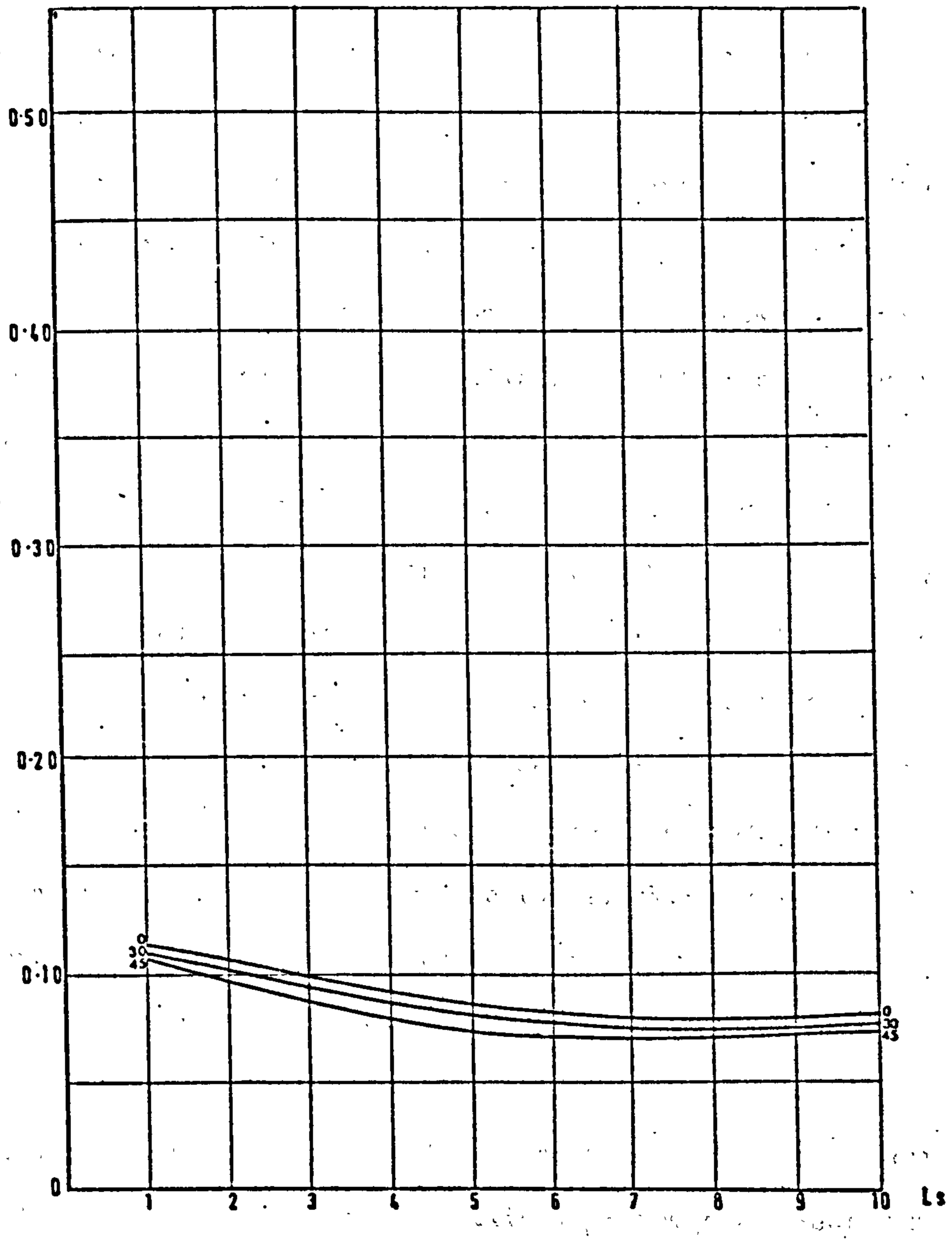


DIAGRAM 6.28: RELATIONSHIP BETWEEN THE LOCALISATION FACTOR, F, AND SPACE SIZE FOR DIFFERENT ORIENTATIONS OF BLOCK LENGTH 20.

CONCLUSIONS

The concept of a measure of the exposure profile rests on the spatial variability of exposure. In this sense, it has a great potential for discerning characteristic attributes of flow in relation to form. Such a measure is useful in a design situation where comparative and evaluative studies are attempted. In such cases, special non-dimensional descriptors may be necessary so that comparison is possible between forms, in which dimensions may change, but not relative dispositions or locations. Topological measures of form can prove to be of great use in this context. An exposure profile is a measure of flow which can be extremely sensitive to changes in relevant form aspects. A study of profiles may yield a large body of information, which could be difficult and impractical to use. By ignoring certain quantitative aspects of the profile measure, this information is greatly reduced without loss in its usefulness. This may be finally summarised in a profile morphology.Numerical measures can be derived from the profile to describe the localisation of the exposure, i.e., the concentration of highest exposure values. This could prove to be yet another valuable descriptor of the exposure characteristics of forms. Another attribute of the profile is that it shows the shift, with change in relevant form aspects, of the highest exposure values. A special representation of this aspect may be greatly helped by a topological form descriptor to reveal another useful aspect of form-flow relationships.

CHAPTER VII

SYNTHESIS: THE ENVIRONMENTAL WIND INDEX

1.00 INTRODUCTION

1.01 The individual measures of exposure, non-uniformity and the localisation factor, derived from the exposure profile, have been shown to possess valuable design oriented properties in relating flow to form. Taken individually, they can help to give greater insight into the flow attributes of a given range of forms. It may be convenient, however, to state the flow attributes in a given form by combining the three individual measures, or functions of them, in a single generalised measure. Such a measure, expressed on a numerical scale, can be regarded as an eventual synthesis of the individual measures and a shorter version of their combined properties. It will be called the Environmental Wind Index.

SYNTHESIS OF FUNCTIONS OF THE INDIVIDUAL MEASURES OF FLOW INTO A GENERAL ENVIRONMENTAL WIND INDEX

2.01 The exposure measure, I, the non-uniformity measure, U, and the localisation factor, F, have their counterparts, respectively, as the shelter measure denoted by S, the uniformity measure, denoted by O and the non-localisation factor, denoted by D. Since the maximum values of each of I, U and F are 1 then S, O and D can be defined as:

$$S = (1 - I)$$

$$O = (1 - U)$$

and

$$D = (1 - F)$$

2.02 The Environmental Wind Index, C, can be defined as the product of the shelter measure, the uniformity measure and the non-localisation factor. It can be stated as:

$$C = (1 - I)\ (1-U)\ (1 - F)$$

or $$C = S\ O\ D$$

2.03 The physical interpretation of C is that as a measure of non-localised shelter uniformly distributed througout the relevant space. Therefore, it is essentially a measure of the shelter properties in the space. It does not only take the average property of shelter, but also considers whether the local values of the shelter properties are uniform and non-localised through the space. It takes values greater than zero and less than one. The higher the value of C, the greater the shelter properties of the space. Higher values of O and/or D would augment the generalised value of S, and, therefore, that of C. The significance of this property can be greatly appreciated when considering arrangements with the same value of the average shelter, S. In such arrangements, the application of the Environmental Wind Index, i.e., introducing the uniformity and non-localisation properties, would either differentiate between their shelter properties or consolidate the similarity in their wind conditions.

COMPUTATIONS OF THE ENVIRONMENTAL WIND INDEX FOR THE INVESTIGATED ARRANGEMENTS

3.01 Using the Environmental Wind Index,values of C were computed for the arrangements studied in the previous chapters. The results, shown in diagrams 7.1 - 7.10 inevitably reflect the internal logic of formulation of the Environmental Wind Index. As such, they seem to show sensible properties of behaviour of wind conditions as a result of the given progression of forms.

3.02 Diagram 7.1 shows the relationship between C and space size for different block lengths at normal orientations. The highest values of C

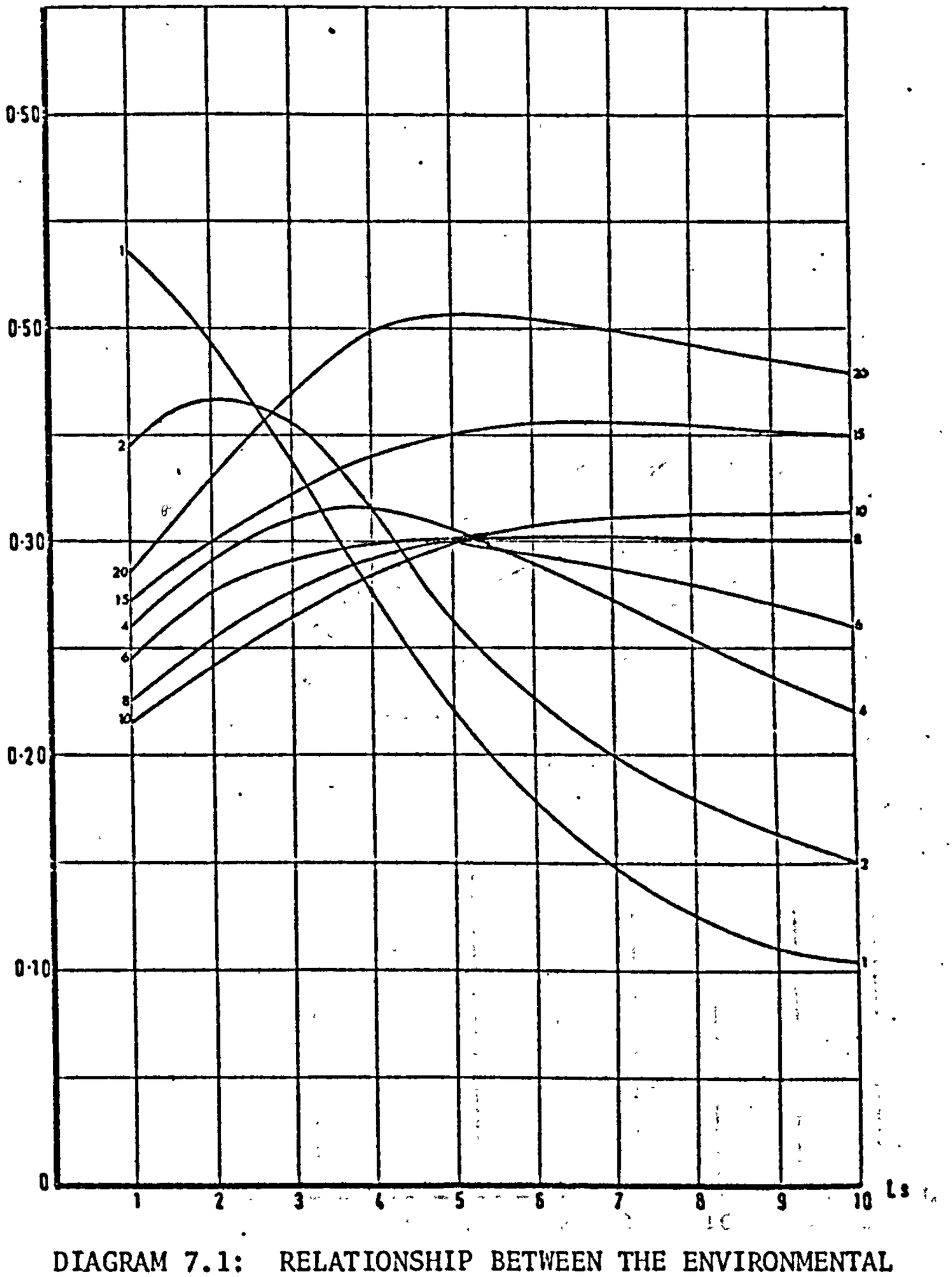


DIAGRAM 7.1: RELATIONSHIP BETWEEN THE ENVIRONMENTAL WIND INDEX, C, AND SPACE SIZE, L_s, FOR DIFFERENT BLOCK LENGTHS (1 to 20) AT ORIENTATION 0°.

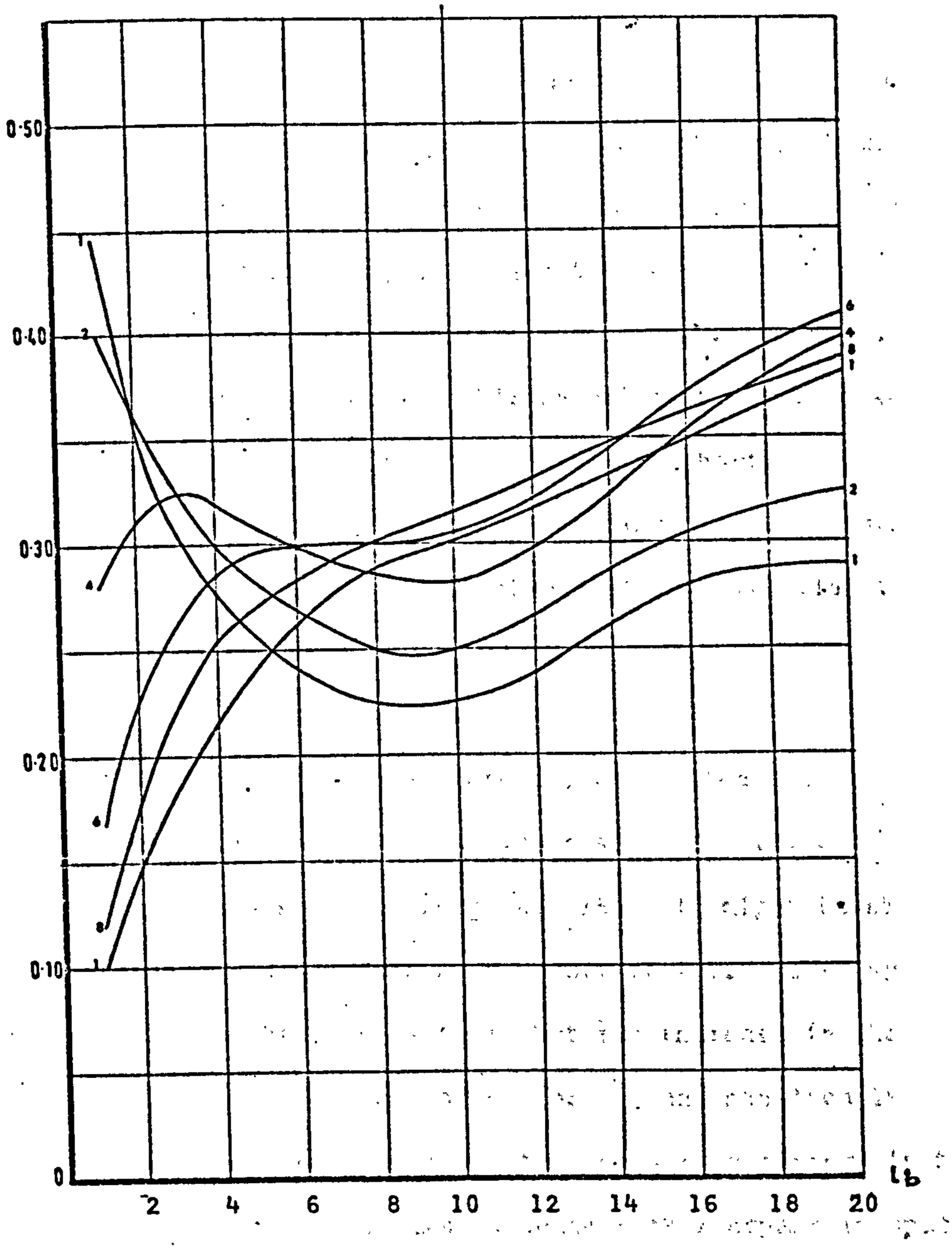


DIAGRAM 7.2: RELATIONSHIP BETWEEN THE ENVIRONMENTAL WIND INDEX, C, AND BLOCK LENGTH FOR DIFFERENT SPACE SIZES AT ORIENTATION 0°.

occur at smaller spaces for shorter block lengths but at larger spaces for larger blocks.

3.03 Diagrams 7.3 - 7.10 show the relationships between C and space size at different orientations for block lengths 1, 2, 4, 6, 8, 10, 15 and 20. For block lengths 1- 4 oblique orientations show lower values of C than the normal orientations. For block lengths longer than 4 higher values of C are shown by oblique orientations at smaller spaces, but as the space size increases, the situation is reversed and oblique orientations take lower values of C. The range of values of C is highest for shorter block lengths but decreases as the block length increases. At block length 1, orientation 0°, the range for C is about 0.37, whereas it is only 0.15 at block length 15 for the same orientation.

3.04 The graphs show interesting and, perhaps, unexpected patterns of values and behaviour. An example of this is the increase in the value of the EWI towards larger spaces at block length range 8 - 15. It might be expected that the shelter values would decrease as a result of increase in space size. Up to a certain extent this is true, but the increase in the values of EWI are attributed to higher values of uniformity and non-localised exposure conditions. An example of a contrasting behaviour pattern is block length 1. In this case, the EWI values decrease with increase in space sizes. The decrease is characterised for most of the range by relatively steep gradients. This effect is due to the combined effect of decrease in the values of the three components of the EWI with increase in space size, i.e., as the space increases for short block lengths the shelter values, the uniformity and the non-localisation values decrease jointly.

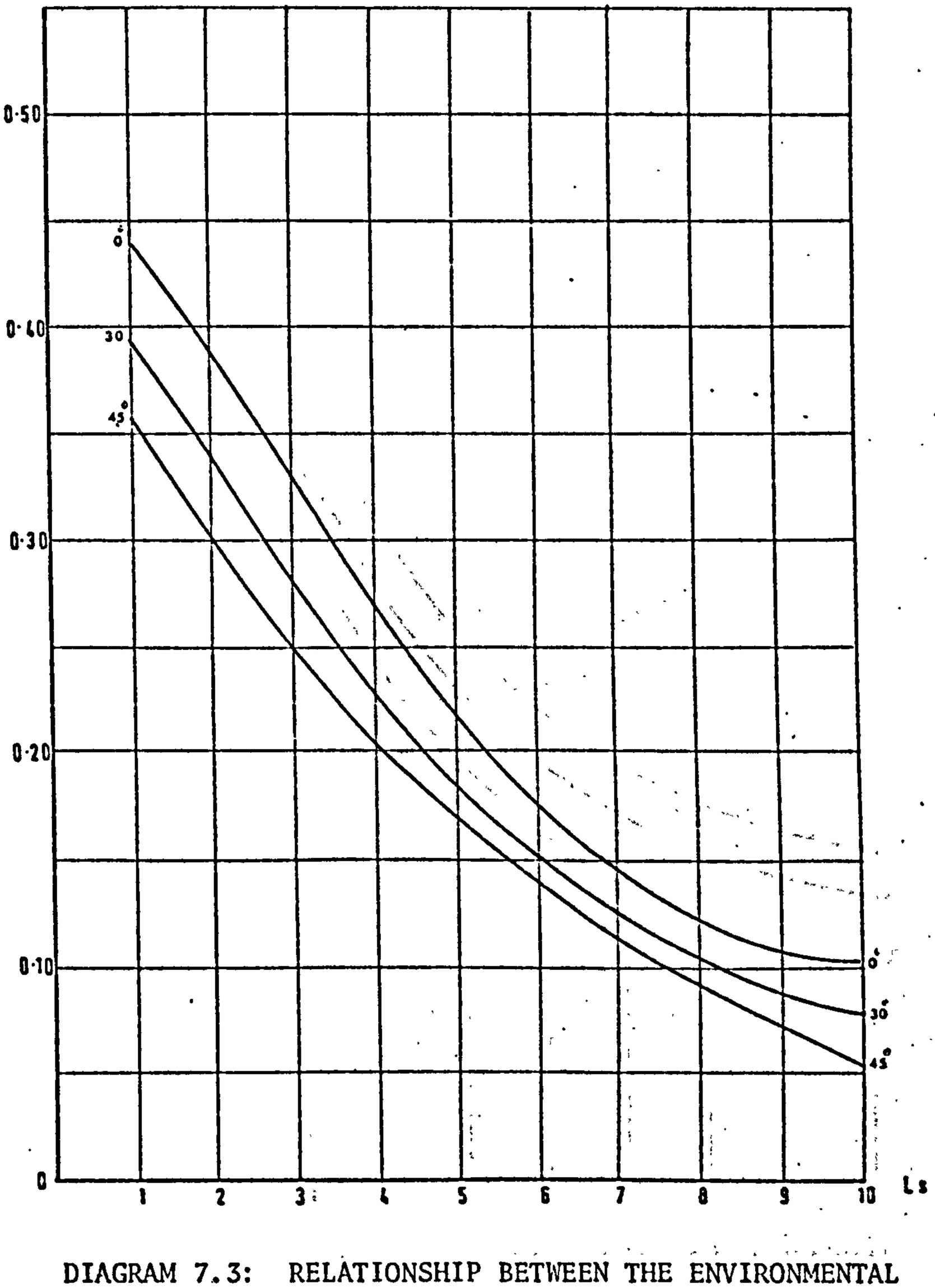


DIAGRAM 7.3: RELATIONSHIP BETWEEN THE ENVIRONMENTAL WIND INDEX, C, AND SPACE SIZE AT DIFFERENT ORIENTATIONS OF BLOCK LENGTH 1.

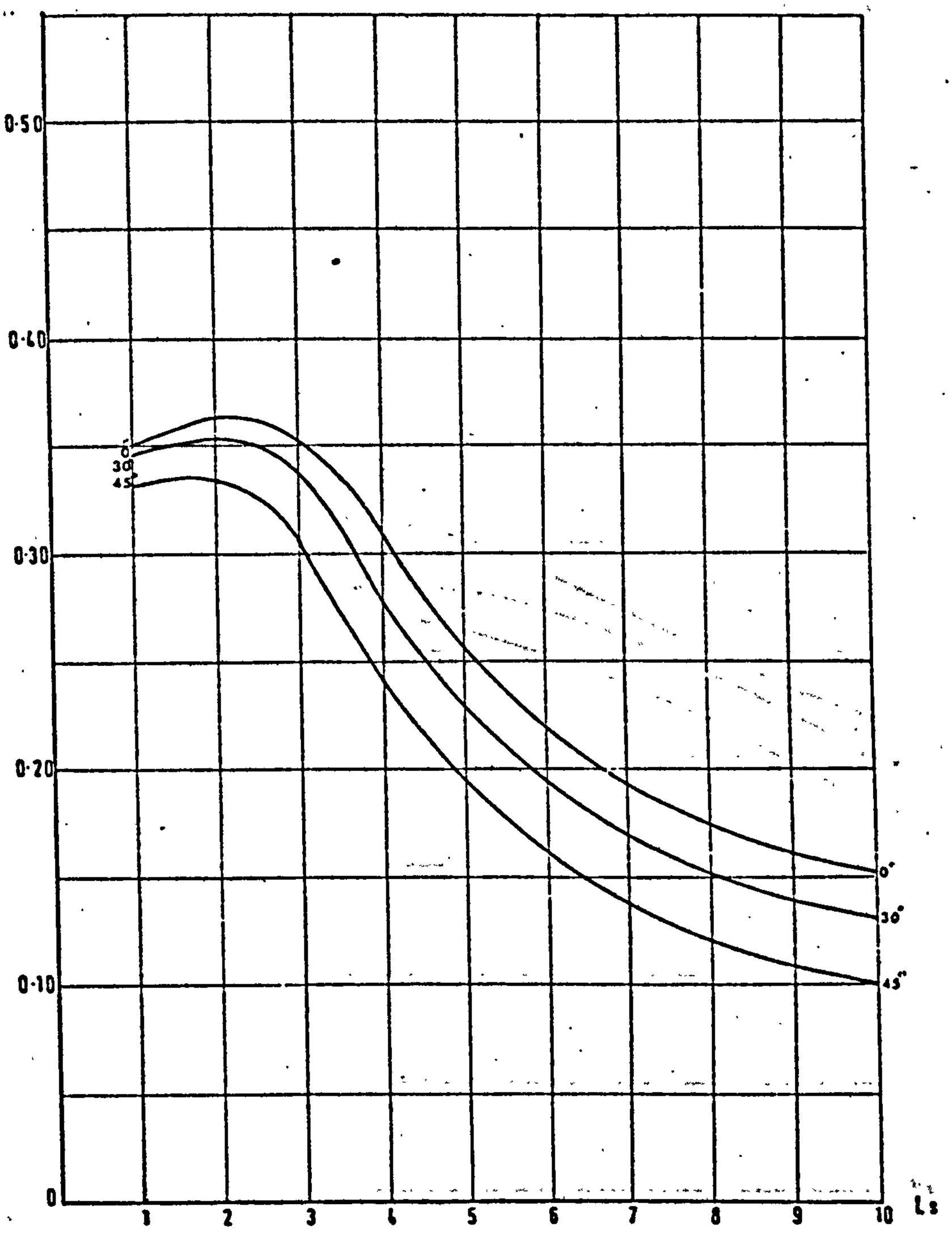


DIAGRAM 7.4: RELATIONSHIP BETWEEN THE ENVIRONMENTAL WIND INDEX, C, AND SPACE SIZE AT DIFFERENT ORIENTATIONS OF BLOCK LENGTH 2.

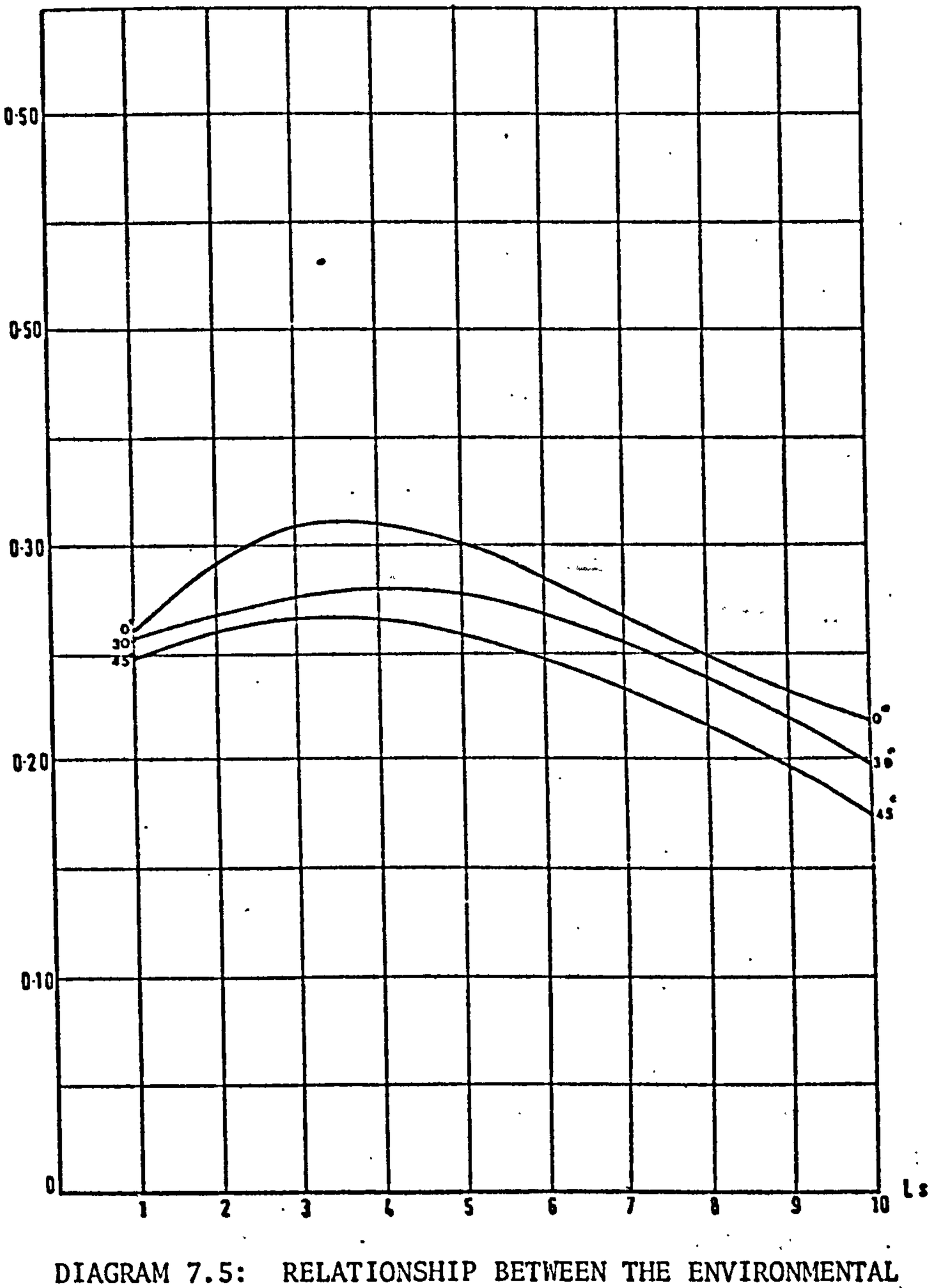


DIAGRAM 7.5: RELATIONSHIP BETWEEN THE ENVIRONMENTAL WIND INDEX, C, AND SPACE SIZE AT DIFFERENT ORIENTATIONS OF BLOCK LENGTH 4.

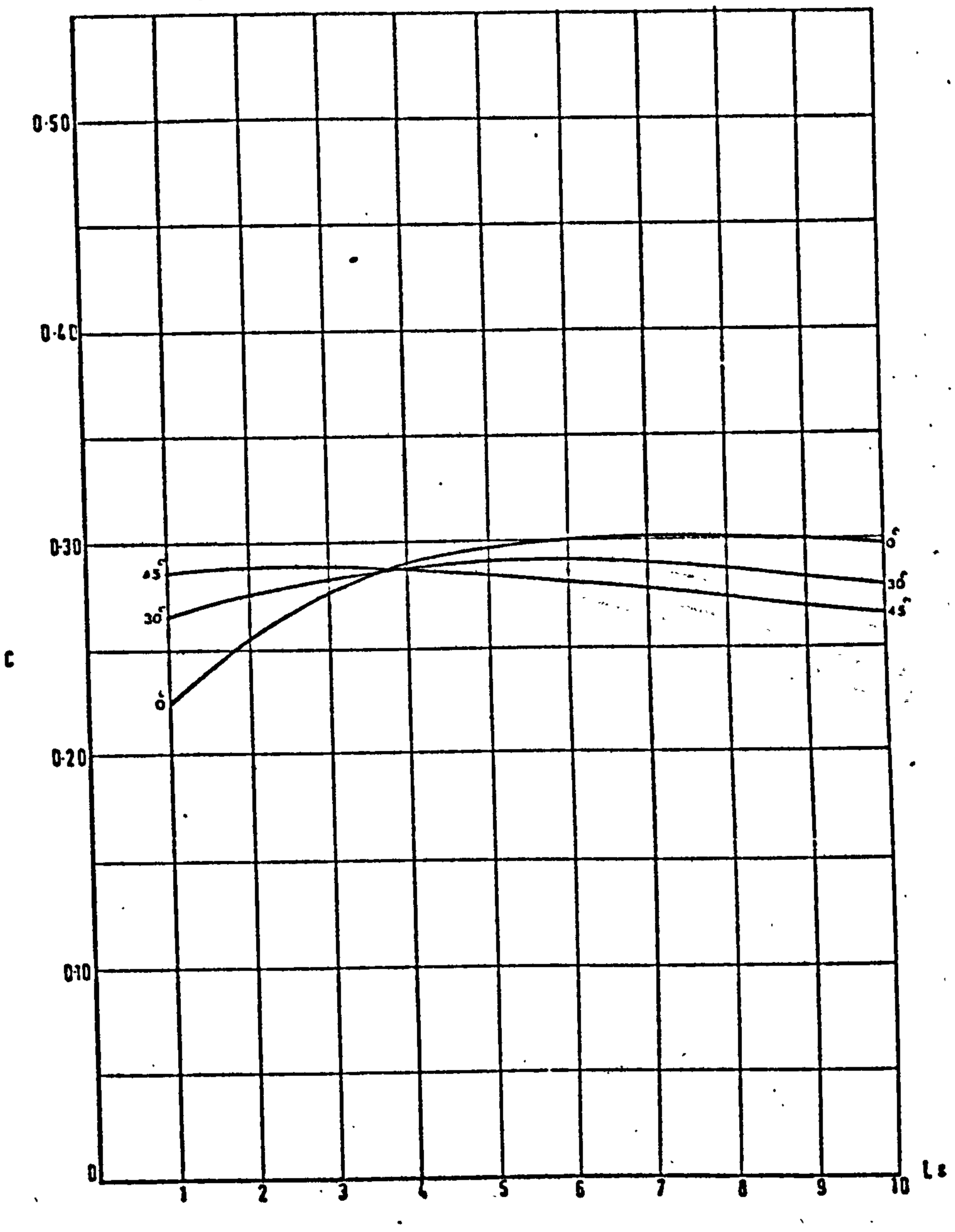


DIAGRAM 7.6: RELATIONSHIP BETWEEN THE ENVIRONMENTAL WIND INDEX, C, AND SPACE SIZE AT DIFFERENT ORIENTATIONS OF BLOCK LENGTH 6.

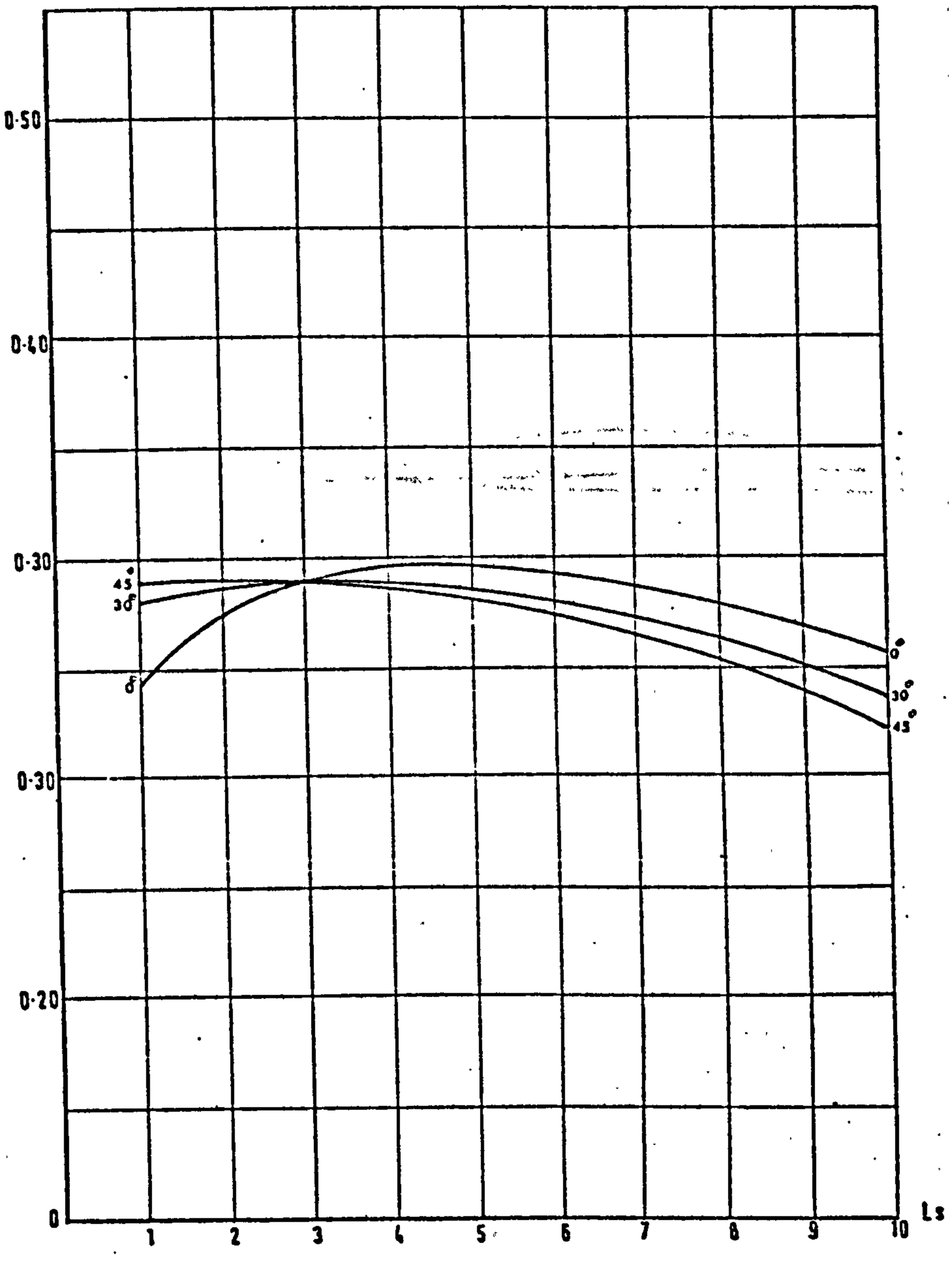


DIAGRAM 7.7: RELATIONSHIP BETWEEN THE ENVIRONMENTAL WIND INDEX, C, AND SPACE SIZE AT DIFFERENT ORIENTATIONS OF BLOCK LENGTH 8.

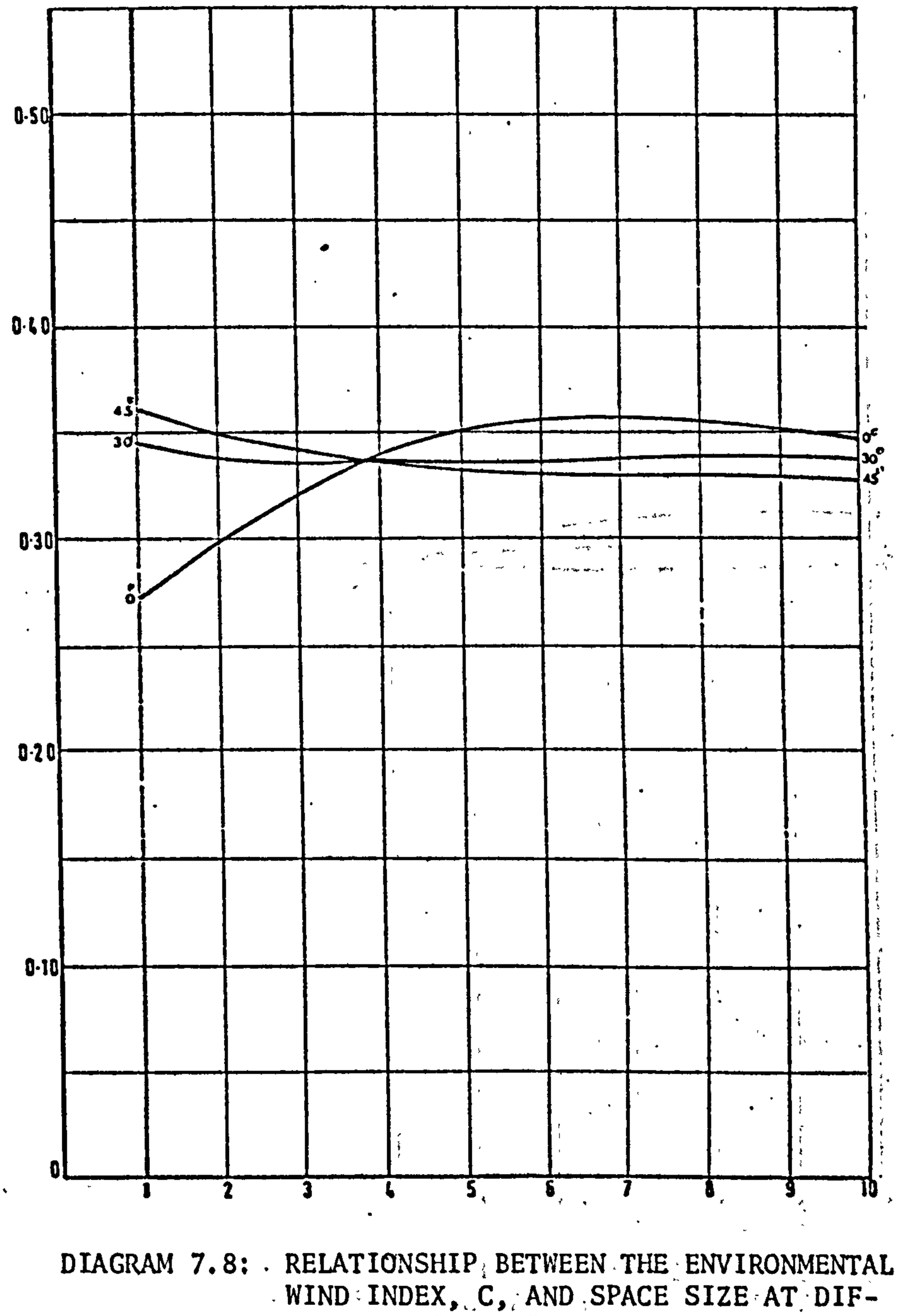


DIAGRAM 7.8: RELATIONSHIP BETWEEN THE ENVIRONMENTAL WIND INDEX, C, AND SPACE SIZE AT DIFFERENT ORIENTATIONS OF BLOCK LENGTH 10.

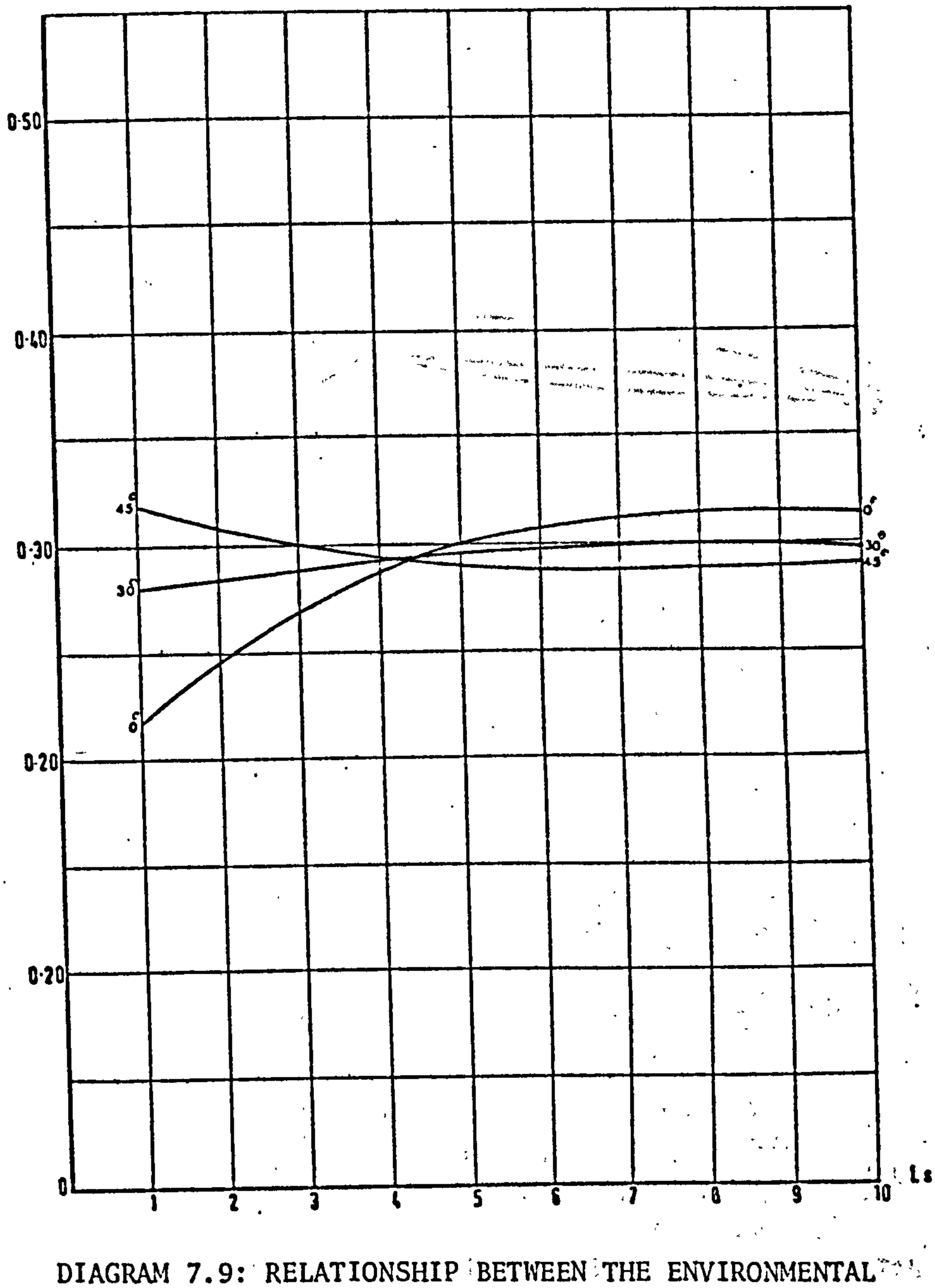


DIAGRAM 7.9: RELATIONSHIP BETWEEN THE ENVIRONMENTAL WIND INDEX, C, AND SPACE SIZE AT DIFFERENT ORIENTATIONS OF BLOCK LENGTH 15.

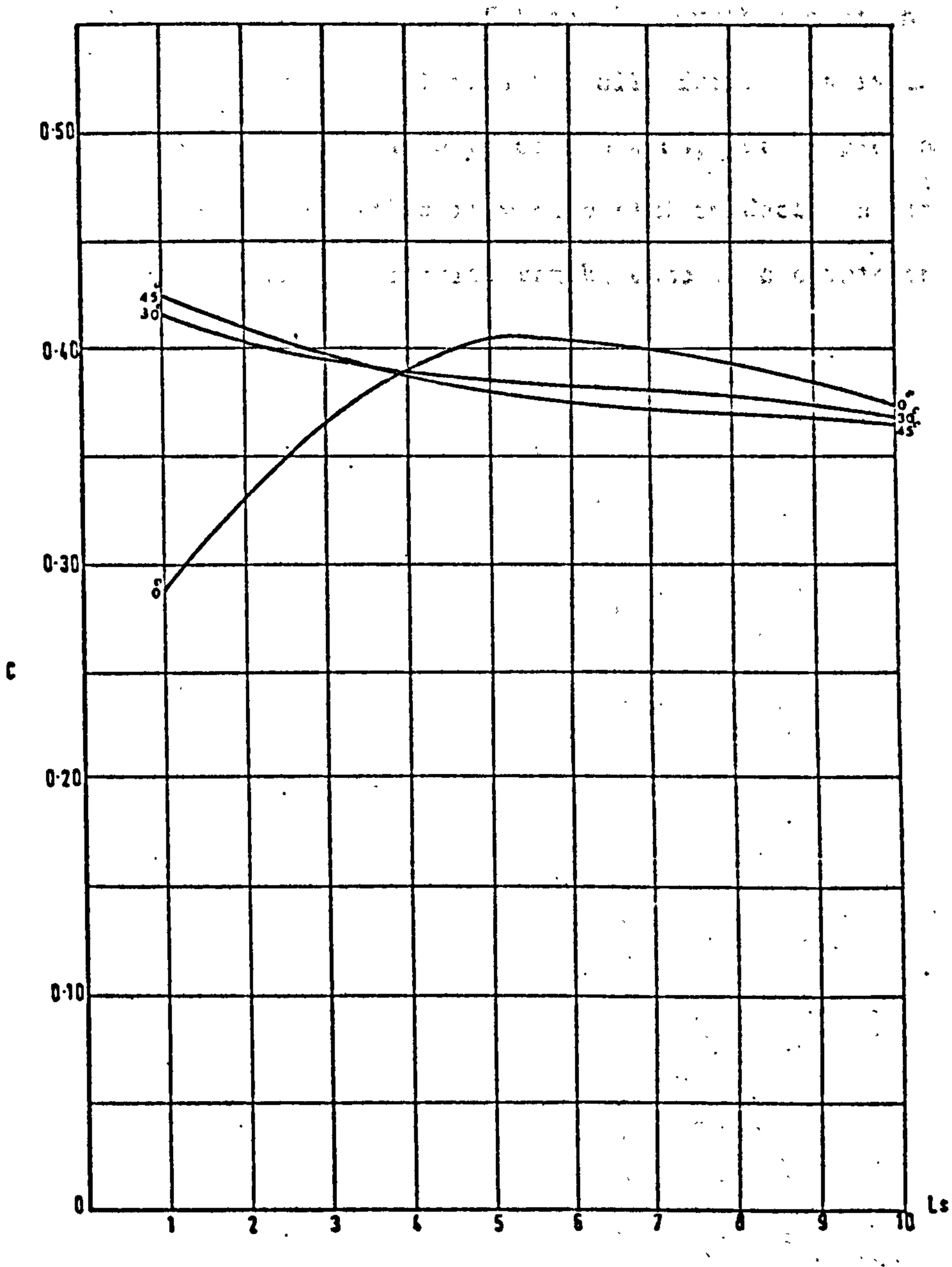


DIAGRAM 7.10: RELATIONSHIP BETWEEN THE ENVIRONMENTAL WIND INDEX, C, AND SPACE SIZE AT DIFFERENT ORIENTATIONS OF BLOCK LENGTH 20.

CONCLUSION

The Environmental Wind Index is a powerful concise synthesis of the design relevant aspects of wind in relation to built form. It is comprehensive by combining the individual aspects of the wind, yet simple in its formulation. Designers should find it most useful in decision situations where comparison and evaluation of forms can be done on a comprehensive basis.

PART III

DESIGN

CHAPTER VIII

DESIGN APPLICATION OF THE ENVIRONMENTAL WIND INDEX

1.00 INTRODUCTION

1.01 The practical limitations of developing the descriptors of wind flow in the preceding chapters have made it convenient to use a two-dimensional vertical plane in which the condition of the wind was described. The problem faced in real design situations is more complex. Spatially, it is three-dimensional and temporally it is changing on a micro-time scale as well as seasonally. Further, the requirements that the wind conditions should satisfy vary according to the users' activity systems, activity locations and patterns in time. In this cahpter, the measures of wind will be considered in relation to their design application. Since it is impossible to conceive of all possible design situations in this respect, the discussion here will centre on a theoretical model whose components represent the essential structure of a design situation where wind and built form are considered.

DESCRIPTION OF THE DESIGN SITUATION

2.01 The significance of the wind condition in relation to built form stems from its effect on human comfort and hygiene requirements, and on the needs of certain activities, e.g., tennis. The users of a built form undertake a range of activities which may relate to work, leisure, etc. The range of activities may be regarded as requiring a compatible range of wind conditions in designated regions of the built form. Assume that an activity, A_i, taking place in the region, R, of a built form (indoor or out) at time, t, (which describes both time and duration) requires a specified wind environment E_{i+} concomitant with it in place and time. This can be represented by the symbolism:

$$[A_i : R, t] \rightarrow [E_{i+} : R, t]$$

2.02 The activity is assumed to take place in a modified space (as a result of putting up a built form). It is not important at this stage to say whether the activity is going to take place inside or outside the built form, since the wind conditions of the site are not conducive to it or to satisfying the user's requirements and a built form has to be put up. Therefore, a built form, B, has to be put such that it acts on the initial wind condition in the site, E_s, to produce the required wind conditions necessary to the activity A_i. This can be formulated as:

$$B[E_s : R, t] \rightarrow [E_{i+} : R, t]$$

2.03 From the above it can be seen that the components of the design situation are:

a) activity.

b) temporal specification of the activity.

c) spatial specification of the activity (in relation to the built form).

d) a required condition of the wind to be achieved.

e) an initial condition of the wind existing on the site and specified temporally and spatially.

f) a built form which changes the unfavourable wind conditions of the site to favourable ones.

THE MODEL

3.01 The designer, having considered the components of the design situation, will proceed to try and achieve the requirements through an extensive search and manipulation of the appropriate aspects of the form with the help of a wind tunnel (or computer).

The main problem in the search for the wind flow characteristics of the

built form is how to define the space contingent with it by regions to each of which an environmental wind index can be ascribed. For the purposes of this model, a conceptual form is specified as being topologically equivalent to any built form in that it divides space into two distinct spaces: in-space and out-space. This conceptual space is shown in diagram 8.1.

3.02 In developing this model, set theoretic symbolism is adopted on account of its capacity to bring out more clearly the relationships between the different elements.

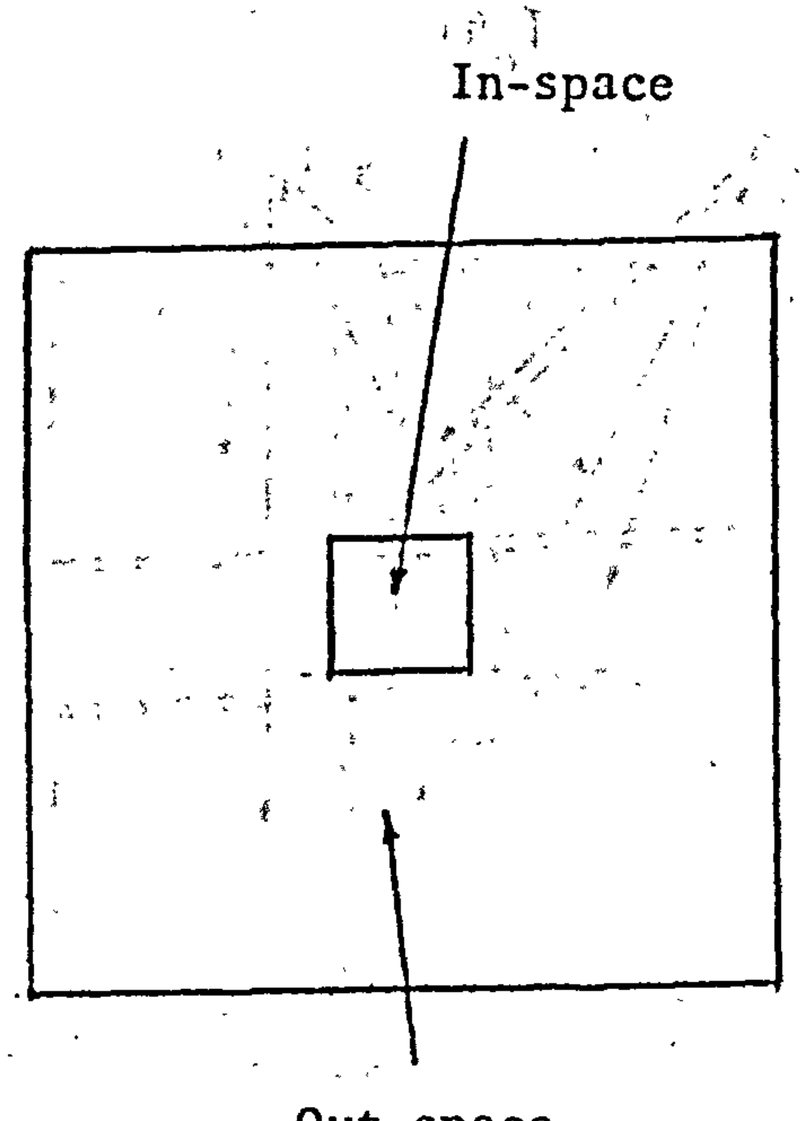
3.03 Taking the out-space, such space can be divided into two sets of regions. A set of proper regions $[R_p]$ and a set of ambiguous regions, $[R_a]$, diagram 8.2. The difference between proper and ambiguous regions is that proper regions are those which can be properly related to the form functionally or geometrically, whereas the ambiguous regions constitute that part of the out-space which, although spatially related to the built unit, has not been explicitly specified by the user or the designer. This, however, is not an absolute condition since other classification schemes can be worked out and the space in the environs of the built form can thus be broken into categories which are meaningful from the viewpoint of assigning an environmental wind index. In this respect, the most important factor, however, are the functional consistency, from the point of view of the activity, and geometric continuity. Denoting the out-space by B_o and the in-space by B_i (to emphasise that its existence is due to the built form, B), we have (see diagram 8.2):

$$B \equiv [B_o], [B_i]$$

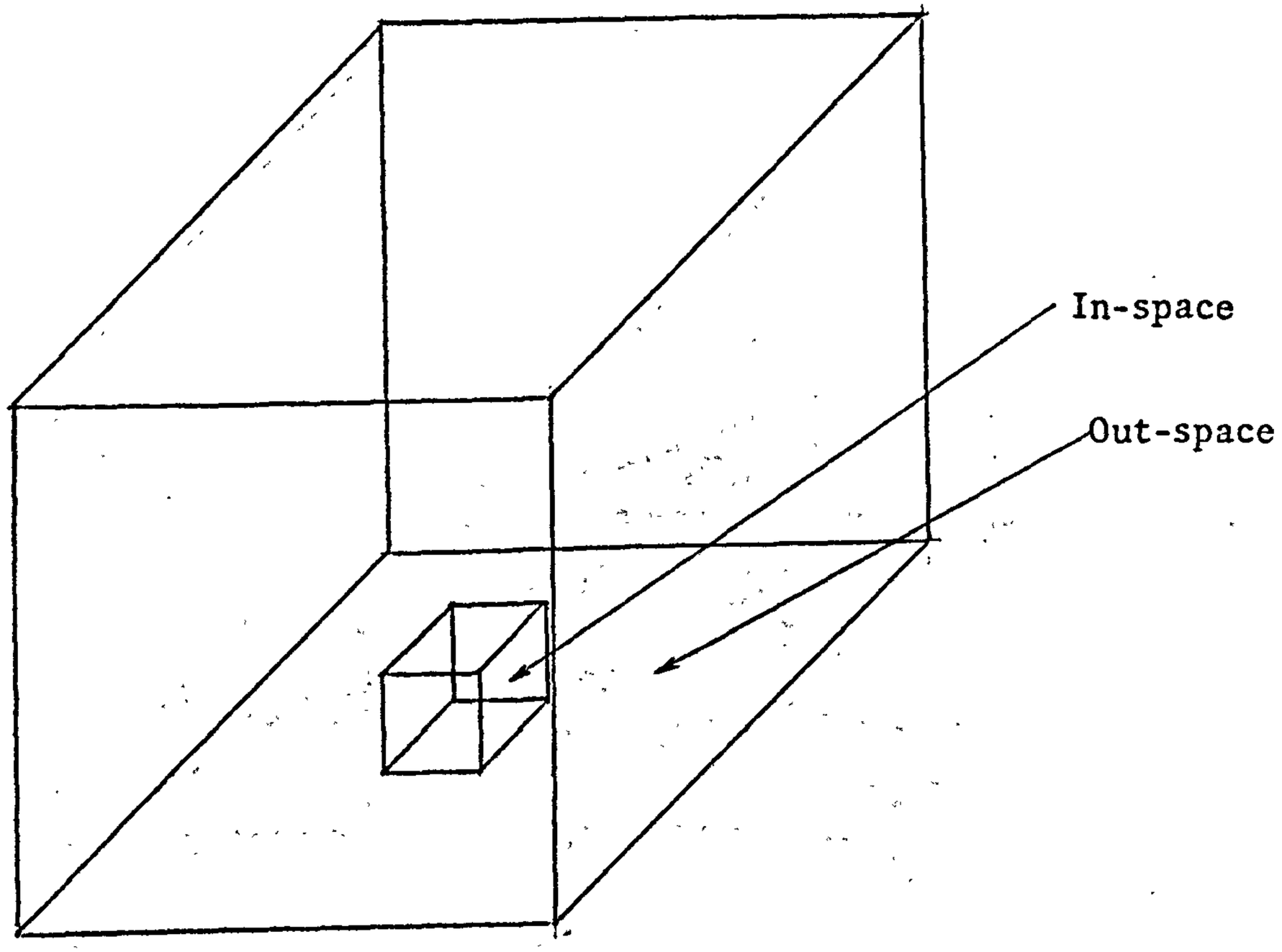
Taking $[B_o]$ as equal to its component proper and ambiguous regions, we have:

$$B_o \equiv [R_p]_o \cup [R_a]_o$$

DIAGRAM 8.1: CONCEPTUAL FORM AS TOPOLOGICALLY EQUIVALENT TO BUILT FORM

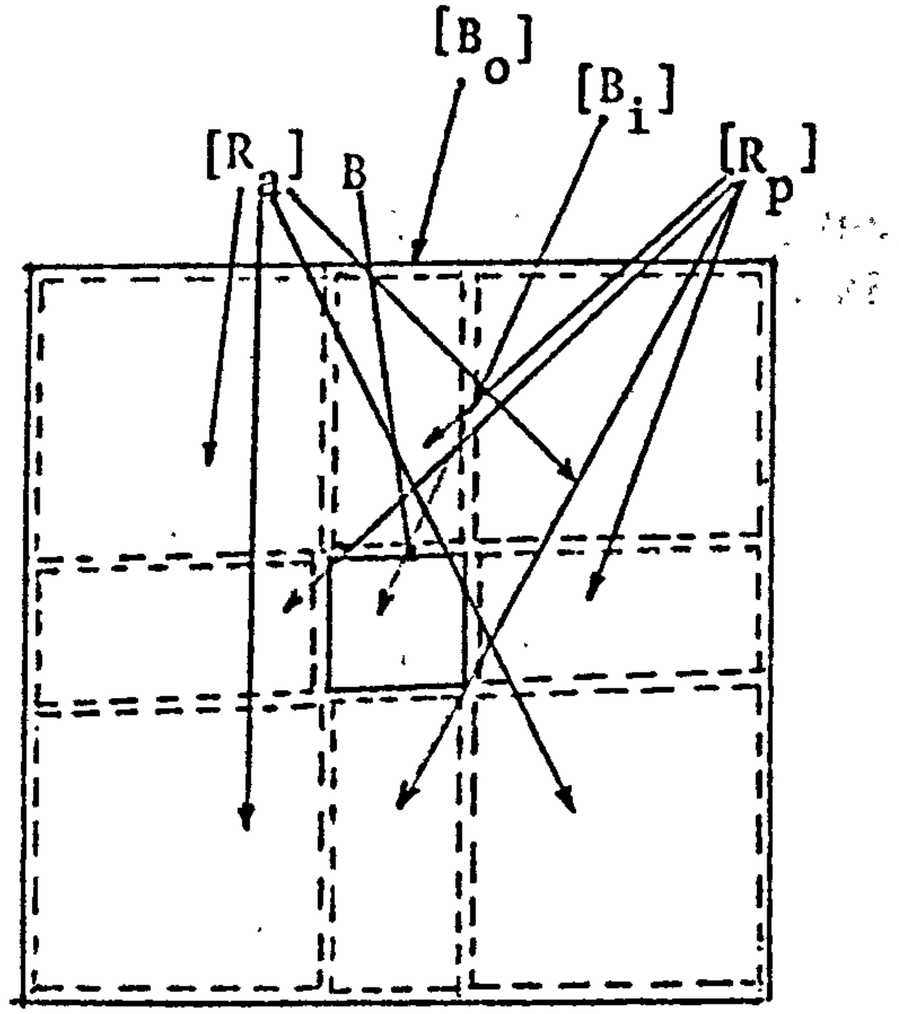


PLAN



N-DIMENSIONAL

DIAGRAM 8.2: CONCEPTUAL SPACE SUBDIVIDED INTO REGIONS TO EACH OF WHICH AN ENVIRONMENTAL WIND INDEX CAN BE ASCRIBED



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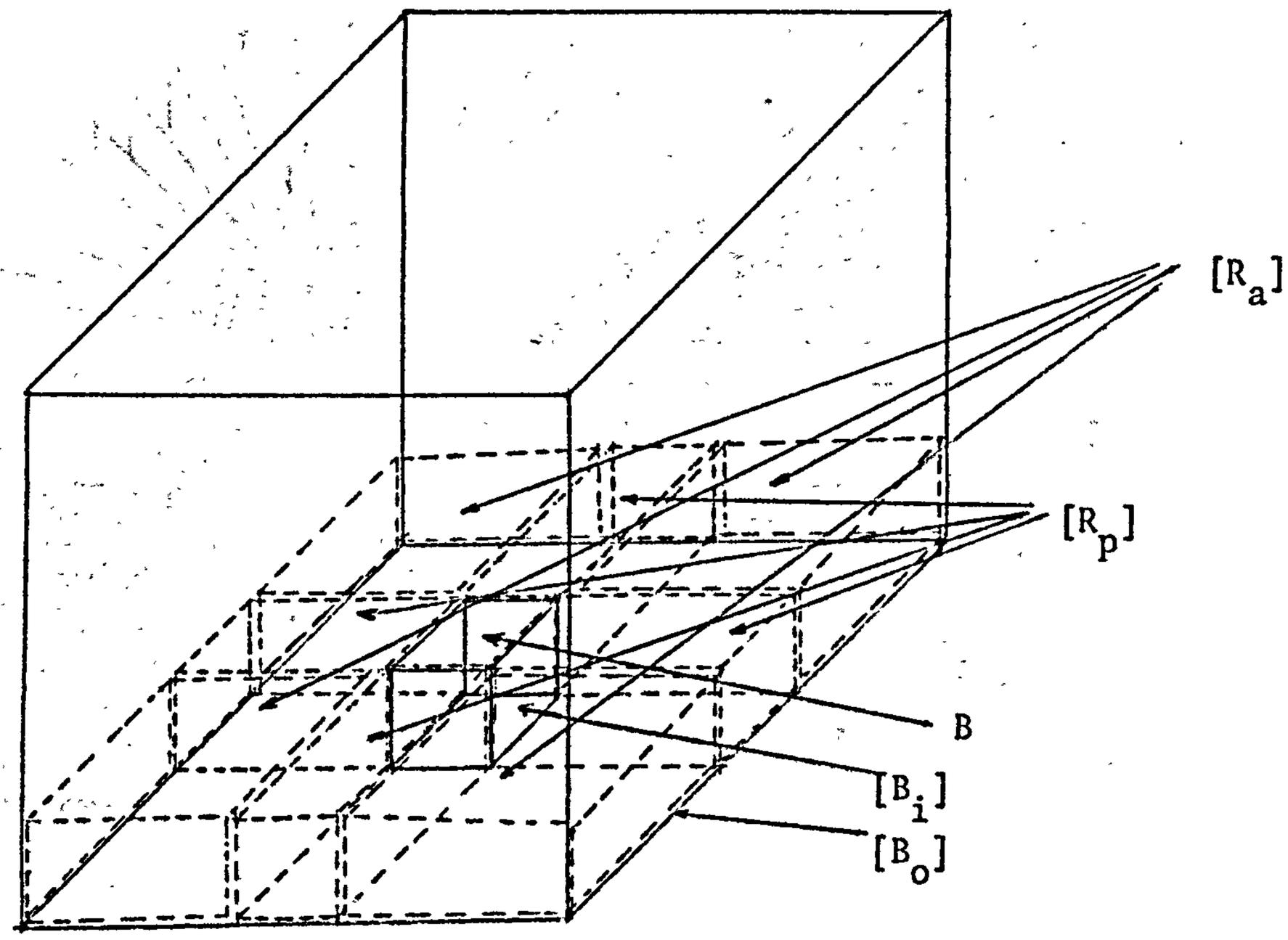


N-DIMENSIONAL

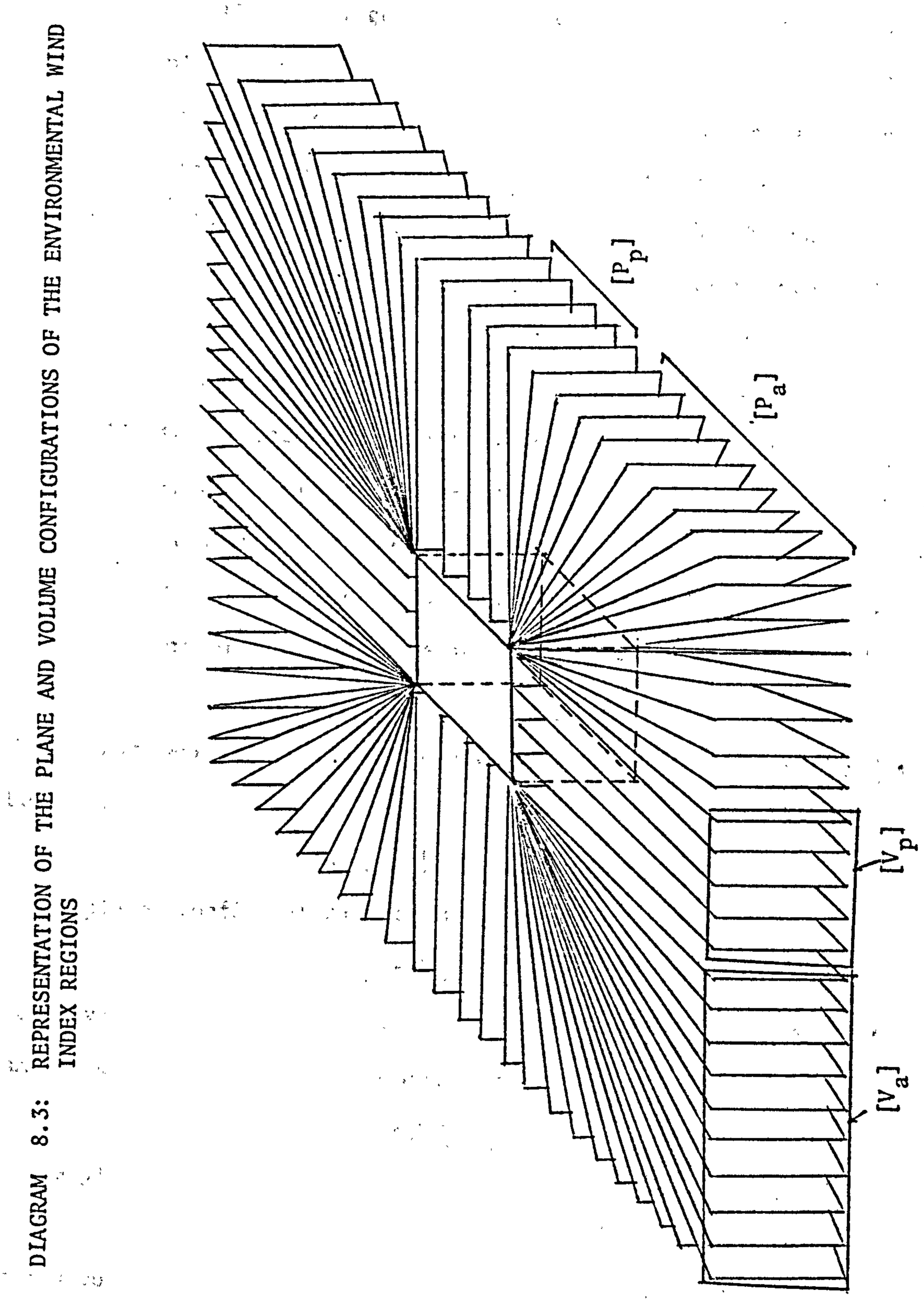


DIAGRAM 8.3: REPRESENTATION OF THE PLANE AND VOLUME CONFIGURATIONS OF THE ENVIRONMENTAL WIND INDEX REGIONS

3.04 There are two configurations for ascribing the Environmental Wind Index to the component regions:

a) the first configuration divides each region into a number of planes (vertical or horizontal), diagram 8.3. Each plane emanates from the surface of the built form as a unique reference point. The planes constitute the planes for the grids of measurements as well as those for the exposure profile. Therefore, for each region a number of environmental wind indices is computed for a series of planes in which the region is divided.

b) the second configuration retains each region as a volume of space. Each region is then divided into a three dimensional grid of measurement. In this case, the environmental wind index is computed for a volume rather than a plane and the exposure profile becomes a surface instead of a line.

3.05 For each region the two configurations are represented by the symbolisms:

$$[R_p]_o \rightarrow [P_p]$$

for a planes configuration with the planes set $[P_p]$, or

$$[R_p]_o \rightarrow [V_p]$$

for a volume configuration with the volumes set $[V_p]$; similarly, for the ambiguous regions of the out-space, we have:

$$[R_a]_o \rightarrow [P_a]$$

for a planes configuration, or

$$[R_a]_o \rightarrow [V_a]$$

for a volume configuration.

3.06 The Environmental Wind Indices of either the planes configuration or

the volume configuration of both the proper and the ambiguous regions lead to a set of Environmental Wind Indices for the whole of the out-space. This can be represented by:

$$[P_p : E_p] \cup [P_a : E_a] \rightarrow [P_o : E_o]$$

for the plane configuration (E_p is the set of indices pertaining to the appropriate set of planes and E_o is the set of indices pertaining to the out-space with a planes configuration P_o). Similarly, for the volume configuration, a set of Environmental Wind Indices can be ascribed to the total out-space in:

$$[V_p : E_p] \cup [V_a : E_a] \rightarrow [V_o : E_o]$$

where E is the set of indices pertaining to the appropriate set of volumes and V_o is the set of volumes constituting the out-space.

3.07 Each of the two sets of Environmental Wind Indices:

$$[P_o : E_o]$$

and

$$[V_o : E_o]$$

are then viewed against the requirement:

$$[E_{i+} : R, t]$$

to decide whether the requirement is satisfied. If the requirement is not satisfied, the form parameters are successively manipulated until the objective criterion is met.

3.08 Computing the Environmental Wind Index may prove of greater value in summarising the data pertaining to its components and can, therefore, make comparison between the different regions much easier. The exposure profile (line or surface) may have greater value, intially, than the other components of the index on account of its visual aspect. This aspect allows the characteristics of the regions to stand out and, therefore, compare more

readily.

By constructing sets of index values over a range of times analogous with t as required by A_i, for a range of forms, an N-dimensional set:

$$[E_{i+} : R, t]$$

can be generated. The search can stop either on reaching the first design which satisfies the condition

$$[A_i : R, t] \rightarrow [E_{i+} : R, t]$$

or it can proceed to generate alternatives.

GENERAL COMMENTS

4.01 It is not difficult to see that the simplest design problem of matching a wind condition due to a built form to that required for a certain activity could prove to be a lengthy and laborious task. The main problem, however, is how to constrain the range of situation that the designer should look into, and in each situation how to reduce the number of regions and/or planes. In facing this problem, the economic criterion, in time and resources, may well be a dominant one.

4.02 The suggestion here that the Environmental Wind Index is to be used for describing the wind condition is open to the criticism that it may not be compatible with the measures of wind-induced comfort criteria, e.g., speed. This is a valid criticism, but in such a situation only the exposure measure can be used and the Environmental Wind Index can be introduced as a further qualification of the wind condition. It can be argued, however, that a wind-induced comfort index can be based on lines similar to those of the Environmental Wind Index. The most important aspect in such a comfort index is the pattern in which people experience wind, within a given space. The spatial variability of the exposure (which the

Environmental Wind Index incorporates) and its influence on the subjective experience of comfort for a moving or a static user may have important bearings on the types of wind environments we can tolerate. As such, the Environmental Wind Index and a similarly formulated comfort index can introduce a dynamic component which incorporates the variability, in space and time, of wind conditions.

CONCLUSION

Due to the infinite range of possible forms and design situations that are related to wind, a conceptual model conceived as topologically equivalent to built forms,has been introduced such that it reflects, with activity and performance specifications, the essential structure of the design situation. The Environmental Wind Index, although developed using a simple two-dimensional plane can be extended to n-dimensions, i.e., treating three dimensional space with time and activity components. The work involved and the format in which results can be expressed should initially concentrate on immediate comprehensibility which can best be achieved by visual representation. The components of the Environmental Wind Index, being more realistic in the description of some design relevant aspects of wind, need be matched with comfort/performance criteria developed on the same line. This, however, is not a condition for its use in design.

C H A P T E R I X

DESIGN WITH WIND:

TWO APPROACHES IN AN URBAN DESIGN CONTEXT

1.00 INTRODUCTION

The lack of sufficient consideration of wind aspects in the design of built form can be attributed to inconclusive and insufficient knowledge. It can also be attributed to designer's attitudes and the value they attach to the potential advantages and disadvantages of air movement conditions in a built form. Both aspects are reflected in the tools with which society organises its physical environment - building codes have a lot to say about the wind aspects that relate to the structure and building fabric, but next to nothing to say about its environmental consequences. In recent years, society and designers as society's agents in this field came to be more aware of the significance of the environmental aspects of wind in relation to built form. The objective of predicting and designing for a better, safer and more congenial wind environment should envisage, in addition to knowledge about wind, a methodology whereby the relevant aspects of wind and form can be appropriately manipulated. As an example, this chapter purports to develop and formalise a procedure to manipulate wind relevant aspects of urban form. The methodological properties of this procedure emphasise the orderly fashion and progression which are essential for the application of the Environmental Wind Index in the design context of a morphological approach. As such, the procedure aims at systematically generating a large set of possible forms whose wind conditions are appropriately monitored (chapter VIII).

PROPERTIES OF THE MODELS

2.01 Design with wind is possible only if sufficient knowledge (measured in terms of reliable predictions) of three main aspects is established:

a) a way of describing wind

b) a way of describing wind relevant aspects of the built form

c) a set of criteria which defines users' requirements in terms of wind conditions created as a result of interaction between wind and built form.

These aspects can be used to point out the main directions of research in the field of air movement and built form.

2.02 In this chapter, two design-decision models are developed on the basis a, b and c, not in real numerical values, but in a conceptual formalism. The two models suggest two approaches which may be consciously applied in a design situation to generate a built form to satisfy a given set of performance criteria.

CONCEPTUAL FRAMEWORK

3.01 The models are heuristic comprising a set of rules or operations governing the interaction between a designer and a machine (a wind tunnel or a computer) to influence spatial distribution of built elements on a site with given wind conditions. They are based on two opposing approaches which can be termed:

a) an accumulative approach (Accumulative Model)

b) an aggregate approach (Aggregate Model)

3.02 The accumulative model defines a set of a number of subsets of locational operations performed on individual built units taken in turn. In this model the location of each built unit is influenced by the location of the unit or units preceding it. It can be described by the symbolism:

$$[L \rightarrow B] = \{[E] : [E] \subset [E]\}$$

3.03 This states that the total number of locational operations, L, operating on a built unit, B, applied to all built units, $[L \rightarrow B]$, leads to a set of environmental wind conditions, [E]. According to a given set of criteria, the set of wind conditions [E] comprises one or more favourable conditions $[E_+]$. The outcome of the model is a spatial distribution of the units in which the wind conditions satisfy the given criteria. The wind condition can be determined by a measure such as the Environmental Wind Index (chapter VII).

3.04 The aggregate model starts with a given initial spatial distribution [B] of built elements, and through successive transformations the distribution that satisfies the criteria is generated. It can be summarised by the symbolism:

$$[L] \rightarrow [B] = \{[E] : [E_+] \subset [E]\}$$

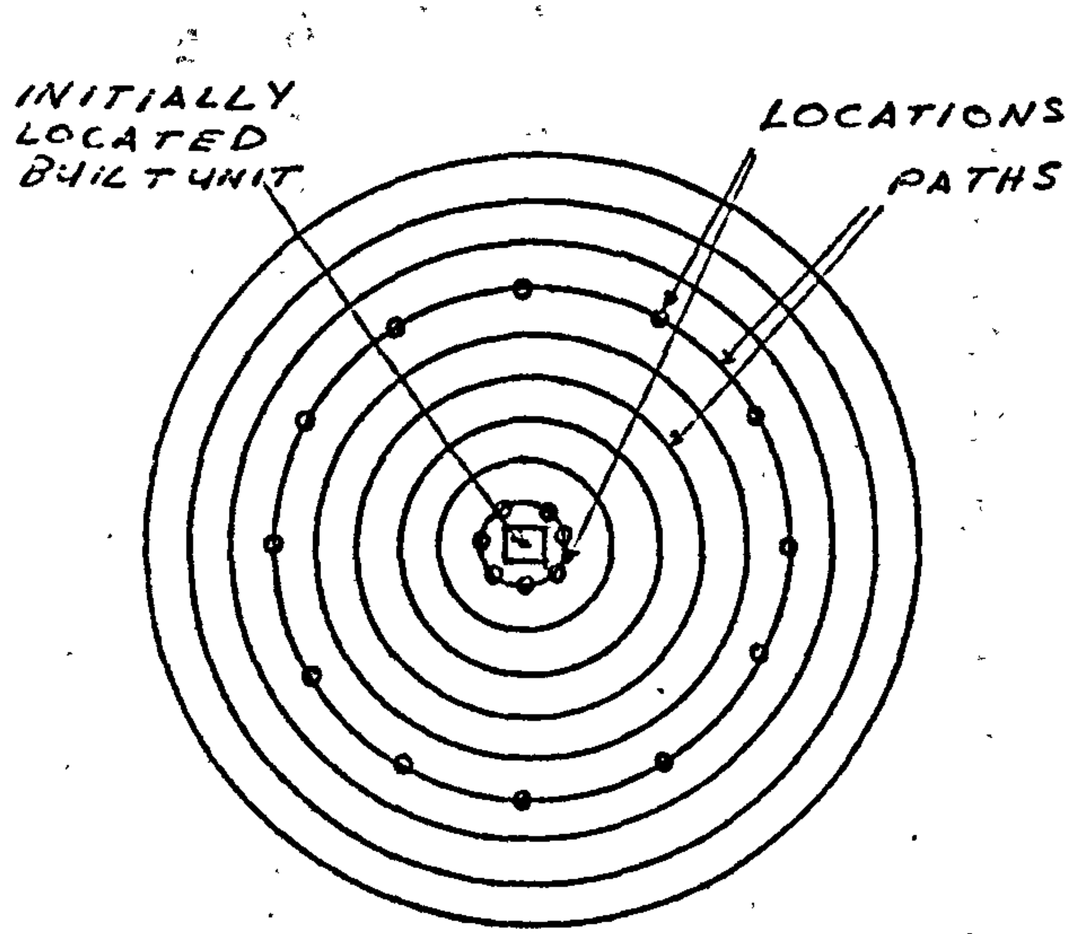
3.05 This states that a set of locational operations, [L], is performed on a set of built units initially aggregated to produce a set of environmental wind conditions [E]. The favourable wind condition, or conditions, $[E_+]$, is contained in [E].

THE ACCUMULATIVE MODEL

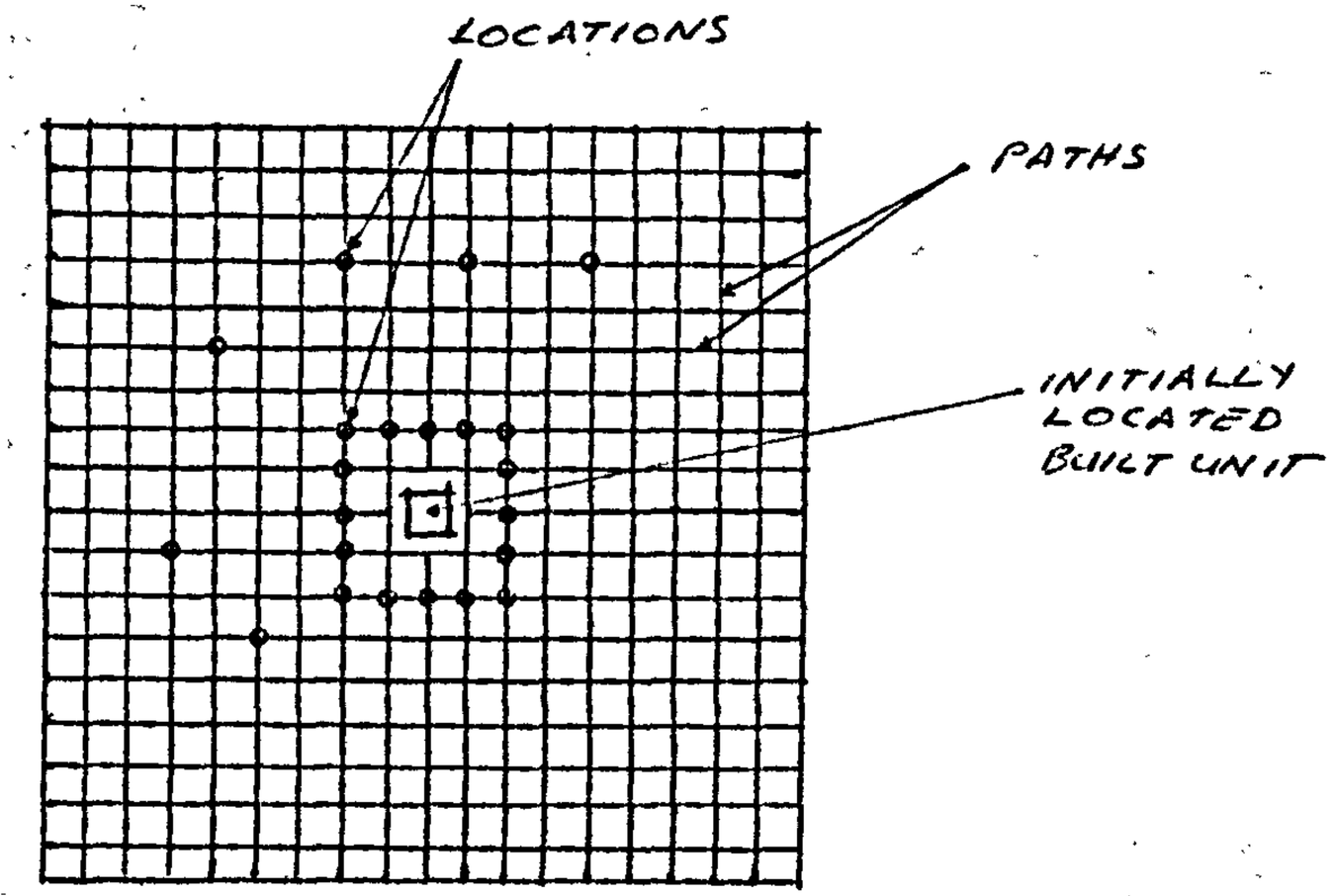
4.01 The model in its simplest formulation:

$$[L \rightarrow B] = \{[E] : [E_+] \subset [E]\}$$

allows for greater articulation in its elements L, B and E. The locational operations can be ordered and guided by a predetermined pattern. Each locational operation can be regarded as having two components: a set of paths and locations on these paths, diagram 9.1. The locational operation follows a path starting at a fixed point depositing the built unit



(a) Locations on Circular Paths.



(b) Locations based on a Square Grid.

DIAGRAM 9.1: GRAPHIC REPRESENTATION OF THE ACCUMULATIVE MODEL

circular. This is not necessary, but it is the simplest way in which locational possibilities can be more readily scanned. Any built unit can be tried for location at all unoccupied locations in the paths. This aspect of the model allows some choice for the designer in that he can choose either the first position that gives E_+ or he can scan the whole locations range to determine the set of acceptable conditions E_+. Where there are other design factors influencing the locations of the units, these possibilities of choice can be very useful for providing alternatives.

4.06 So far the model dealt with only a simple undifferentiated impermeable form with one orientation. Orientation is an important factor in determining E. It can be introduced in the model at the location point level; i.e., given a set, w, of orientations, D, a built unit, B_i, is orientated according to this set at each point it takes and the value of E is determined. Therefore, at this stage, the location of units is determined by the previously located units and orientation. The model takes the form:

$$\{[C], [T]\} \rightarrow \{[D_e], [B_i]\} = \{[E] : [E_+] \subset [E]\}$$

4.07 Again, the designer may be contented with the first location and orientation that satisfy his wind condition criteria. But the availability of alternative orientations can allow for the introduction of other criteria, e.g., sun penetration.

4.08 If we relax the condition of equal dimensions of a unit and introduce a condition of equal volume instead, the units can take different dimensions of sides and, therefore, units do not have to be similar. The ratios of blocks sides are an important form aspect that influences E.

at each location. For each location that the built unit takes on a path, E is evaluated. For the purpose of this development, E is taken to be concerned with external wind conditions. The locational operation can attempt all given locations and paths. As diagram 9.1 shows the location of the first built unit, which is in itself arbitrary for simple undifferentiated forms, can determine the paths along which the search for appropriate locations of other built units may proceed.

4.02 For an initial development of the model it is assumed that the built units are simple blocks undifferentiated within themselves (condition of equal dimensions, e.g., cubes) and undifferentiated from each other (condition of identity). It is also assumed that the units can take only one orientation with respect to the direction of flow and that they are impermeable to the flow. These assumptions simplify the order in which the units are chosen for location. It allows E to be influenced only by the accumulative growth of the group form.

4.03 For a built unit, B_i, location operation L, of components C (paths) and T (locations), is performed for all units, and all paths. This can be represented by:

$$\{[C], [T]\} \rightarrow [B_i]$$

4.04 The outcome of these locational operations may be one or more acceptable values of E, i.e., values of E falling within a prescribed range. We can represent a set of acceptable values of E resulting from this search as E_+ which is the result of the locational operations

$$\{[C], [T]\} \rightarrow [B_i] = \{[E] : [E_+] \subset [E]\}$$

4.05 From diagram 9.1a it can be seen that the location paths are

Introducing a set, n, of possible side ratios, R, that a built unit can take the units can influence E by their accumulative formation, orientation and shape ratios. This development is expressed in the model as:

$$\{[C], [T]\} \rightarrow \{[R_j], [D_e], [B_i]\} = \{[E] : [E_+] \subset [E]\}$$

4.09 The field of choice of the designer is increased further by the introduction of the shape ratio possibilities. The shape ratio aspect operates at the orientation level, i.e., at any location, the set of shape ratio is tried for each orientation, and the values of E determined, diagram 9.2.

4.10 We can proceed to introduce as many relevant form aspects in the model as possible and determine where they can be considered in relation to other aspects. It can be seen that the more aspects we have, the wider the set of possibilities within these aspects, the greater the choice of the designer in influencing E. There are, however, practical difficulties and diseconomies in attempting to investigate all conceivable possibilities. This can be done in two ways:

a) either by introducing other design constraints emanating from other climatic, social or economic aspects of form,

or,

b) by applying a random choice procedure which can be preformed individually or in combinations of the locational operations and the form aspects relevant to wind.

It is important, however, to keep as wide a field of choice as possible, at least at the initial stages of the design. Where the built units are homogeneous and there are no functional constraints on their distribution the units can be, at least initially, organised on purely wind considerations. Such an initial form can be subject to influence from other

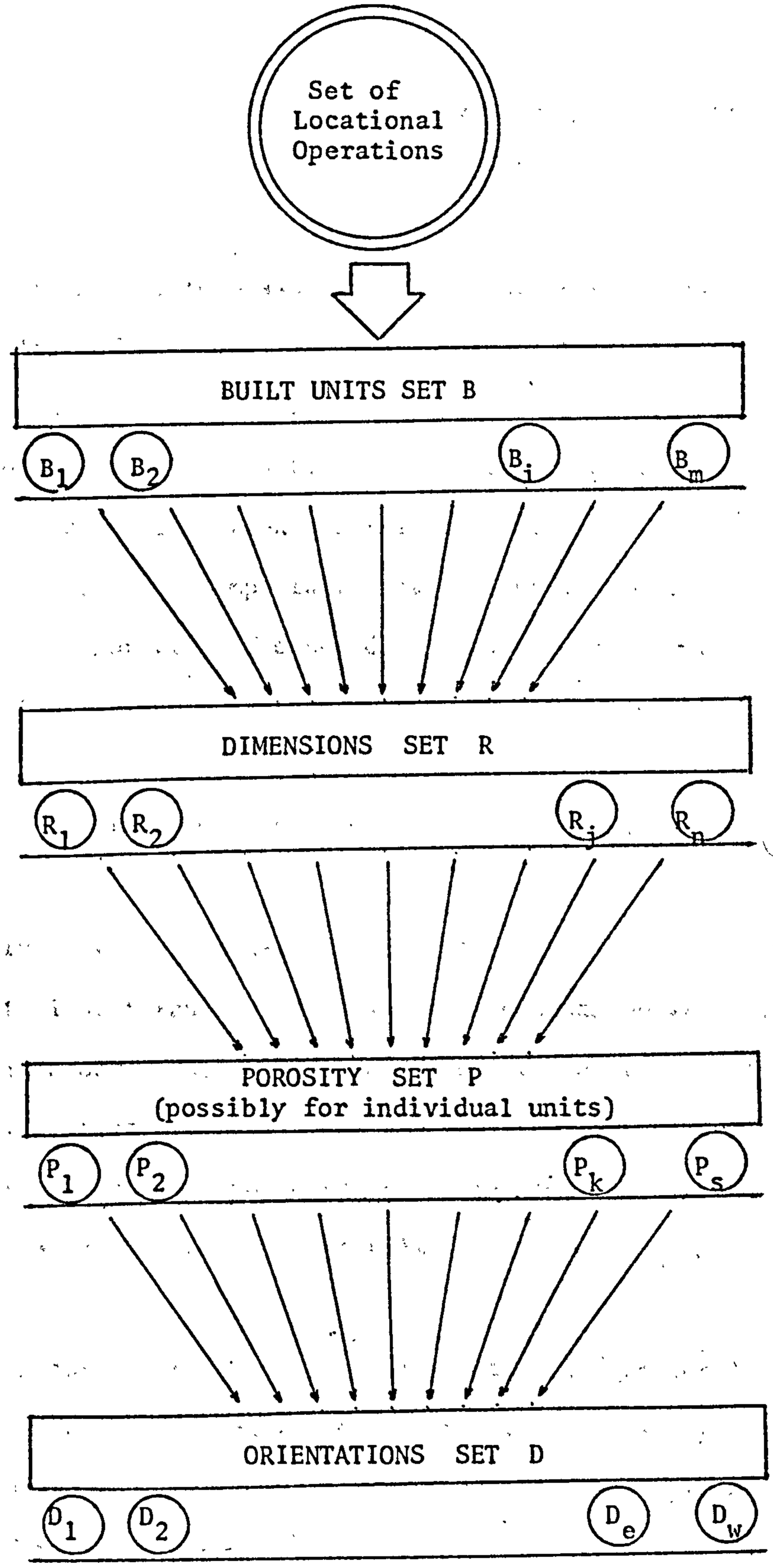


DIAGRAM 9.2: HIERARCHICAL RELATIONSHIP OF LOCATIONAL OPERATIONS AND POSSIBLE FORM ASPECTS OF A BUILT UNIT (ACCUMULATIVE MODEL)

aspects which can be satisfied within a certain range of acceptable E values.

4.11 By specifying the form aspects (more wind relevant aspects, such as the permeability of the units and variations in their shapes, can be introduced), scanning locational operations and measures of wind a spatial distribution of units that satisfies a given range of a set of criteria can be generated with a great degree of objectivity. The wide field of choice is the most important attribute of this model: it allows for the incorporation of other design aspects of climatic, social, economic or aesthetic nature in the subsequent developments of the design.

THE AGGREGATE MODEL

5.01 Contrary to the accumulative model, the aggregate model starts with an initial spatial distribution of built units and manipulates it (taking the units simultaneously rather than individually) until all spatial distribution possibilities are scanned or the given criteria for E arrived at. The following symbolism is used to state the aggregate model (para. 3.04):

$$[L] \rightarrow [B] = \{[E] : [E_+] \subset [E]\}$$

5.02 The main form aspect which is manipulated in this model is the porosity, i.e., the spaces between the built units. This, however, does not mean that other aspects, such as the dimensions, orientations and/or permeability of individual units cannot be introduced, but their introduction on individual built unit basis may prove cumbersome. A possible alternative is to have a spatial distribution of units that are rendered identical in all respects: dimensions, orientation, permeability, etc. This alternative can prove to be too restrictive and it may impose an

unnecessary rigidity on the form. An expedient approach is to introduce the other aspects as random perturbations at each spatial distribution generated by the model operations. This implies that the spatial distribution has the primary role in guiding the generation of the wind form. In practical terms, this will mean that the designer has less components to grapple with. In certain respects this could be the main asset of the model.

5.03 The operations which affect the spatial distribution of the built unit, and, therefore, the porosity of the system have three main components:

a) a way of describing the relative positions of the built units in the distribution.

b) a procedure for methodically changing the locations of the units such that the porosity value is changed.

d) a datum position for the units in the distribution - this acts as the starting point of operations.

5.04 By using two cartesian co-ordinates and mapping each built unit on its geometric plan centre the positions of the units can be defined on an x-axis and a y-axis. So, for a unit j its geometric plan centre can be described on the axes as (x_j, y_j). The whole distribution of n units can be so located and this is symbolised by:

$$\bigcup_{j=1}^{n} (x_j, y_j)$$

5.05 The porosity of the system can be regarded as a function of the summation of the distances separating any element from all other elements averaged over the number of elements. The distance between elements i

and j in the distribution can be defined on the cartesian axes as:

$$\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$$

The distance between element i and all the other elements, n, is given by:

$$\sum_{j=1}^{n} \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$$

and the distance of all elements from all other elements of the system is:

$$\sum_{i=1}^{n} \sum_{j=1}^{n} \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$$

The porosity p of the system can be defined as a function of:

$$p = f \left[\sum_{i=1}^{n} \sum_{j=1}^{n} \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \right]$$

5.06 Clearly, this definition of the porosity aims at taking advantage of parameters which can be manipulated by the requirement b. Therefore, it does not take into consideration the actual sizes of the built units which is the more realistic approach. This, however, can be catered for in the specification of the whole function since the distances are between elements' centres are only a parametric convenience. Further, it might be argued that, since the built elements component of the system remains constant and the proportions of the solids to voids changes, it is this proportional relationship that is more effective in determining the porosity and not the linear spacings of the units. In the absence of empirical evidence, it is, therefore, not easy to say which is a good basis for defining a parameter that satisfies the need for a good form descriptor in relation to wind and at the same time forms a dimensional foundation for the manipulation of the distribution. It is suggested here, since there is no conceptual argument to the contrary, that a measure of porosity usable in the manipulative operations cannot be based on the distances between the units as long as the actual size of the units

is taken into consideration.

5.07 (b) The requirement b can best be achieved by a series of transformations of the initial distribution. The transformations can be expressed as vectors that send a unit from one position to another, but they act on all the units at the same time. This condition of simultaniety cannot be absolute since the essence of the transformation, in terms of changing the porosity values, is to dilate or contract the distribution and, therefore, one or more units have to remain stationary while the rest of the units converge towards them. It is therefore necessary to specify in the locational operations three types of instruction:

1. the intention of the transformation.
2. the extension of the transformation.
3. the stationary unit or units towards which the rest of the units dilate or contract in the distribution.

5.08 The intention of the transformation can further be subdivided into five types:

1.1 dilation of the whole distribution.

1.2 contraction of the whole distribution.

1.3 differential dilation of the distribution in which the transformation dilates parts or sections of the distributions more than others.

1.4 differential contraction of the distribution where sections of the distribution are contracted more than others.

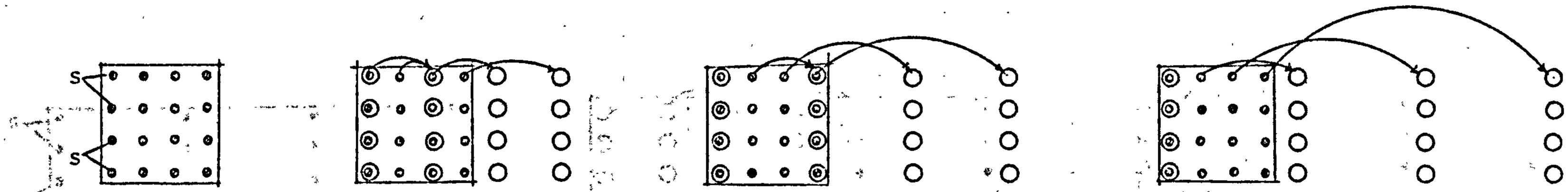
1.5 combined differential dilation and contraction where both dilation and contraction are performed on different sections of the distribution at the same time.

These transformations are shown for hypothetical distributions in diagrams 9.3 - 9.7.

5.09 The transformation can retain the relative disposition of the units in any of the types 1.1 - 1.5 and in this sense the ensuing distributions can, therefore, be topolgocially equivalent to their predecessors. But it can also distort the distribution of sections of the distribution. Such possibilities are shown in diagram 8.8 for a hypothetical distribution.

5.10 The extension of the transformation is a way of describing by how much a contraction or a dilation is less or more than the previous one. It can be expressed as a fraction or a percentage of the separating distances between the built units. It is this aspect which makes a distance-based porosity measure more expedient and aspects a and b above can be directly related in the manipulation of the spatial distribution.

5.11 (c) The third instruction concerns which unit or units remain stationary in the process of manipulation. Such units are shown in diagrams 9.3 - 9.7 where they are indicated by the letter S. In the transformations of the psatial distribution such elements have to be specified otherwise the transformation will only be a translation of the position of the whole distribution with no effect on its porosity. A corrollary of this is that the extension of the transformation is differential. This is so since reducing the distances between successive elements by a certain proportion of the preceding distances between them requires a larger movement by the elements furthest from the stationary unit.

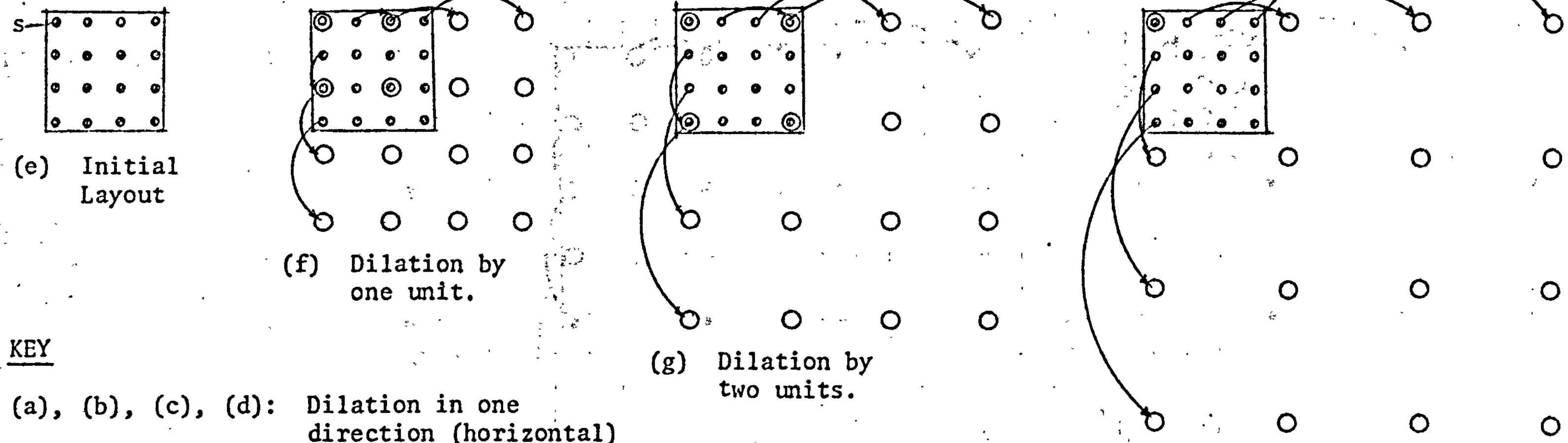


(a) Initial Layout.

(b) Dilation by one unit.

(c) Dilation by two units.

(d) Dilation by three units.



(e) Initial Layout

(f) Dilation by one unit.

(g) Dilation by two units.

(h) Dilation by three units.

KEY

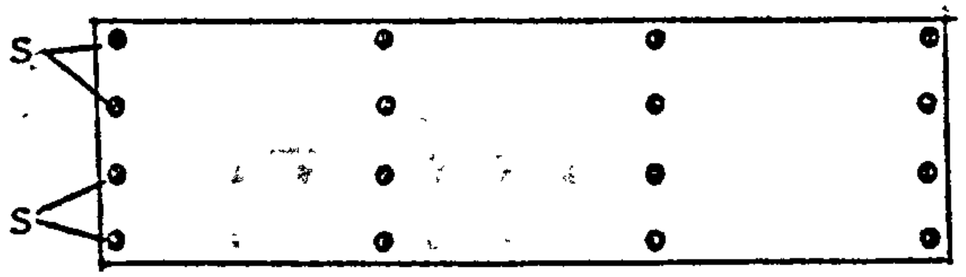
(a), (b), (c), (d): Dilation in one direction (horizontal)

(e), (f), (g), (h): Dilation in two directions (horizontal and vertical)

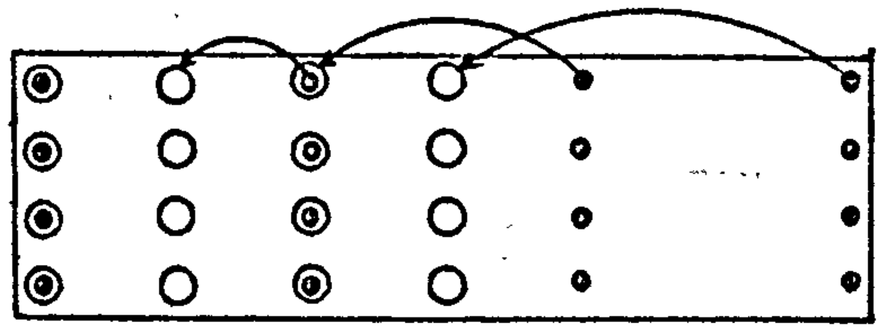
• : Units at initial positions

o : Units position after transformation.

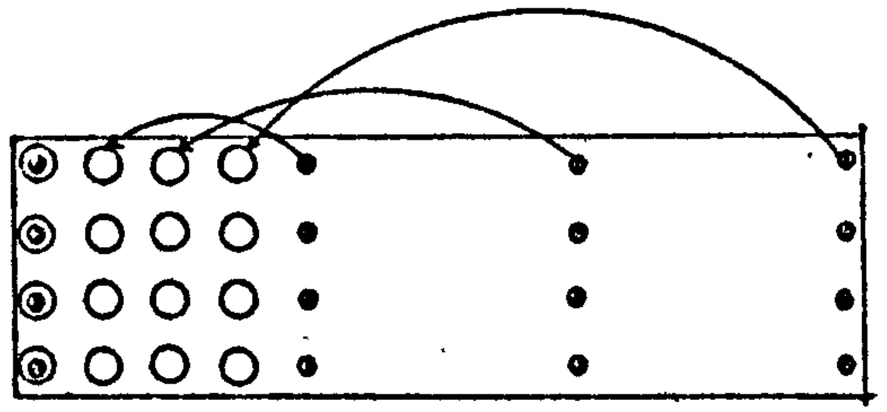
DIAGRAM 9.3: TRANSFORMATION OF THE SPATIAL DISTRIBUTION/BY DILATION OF UNITS.



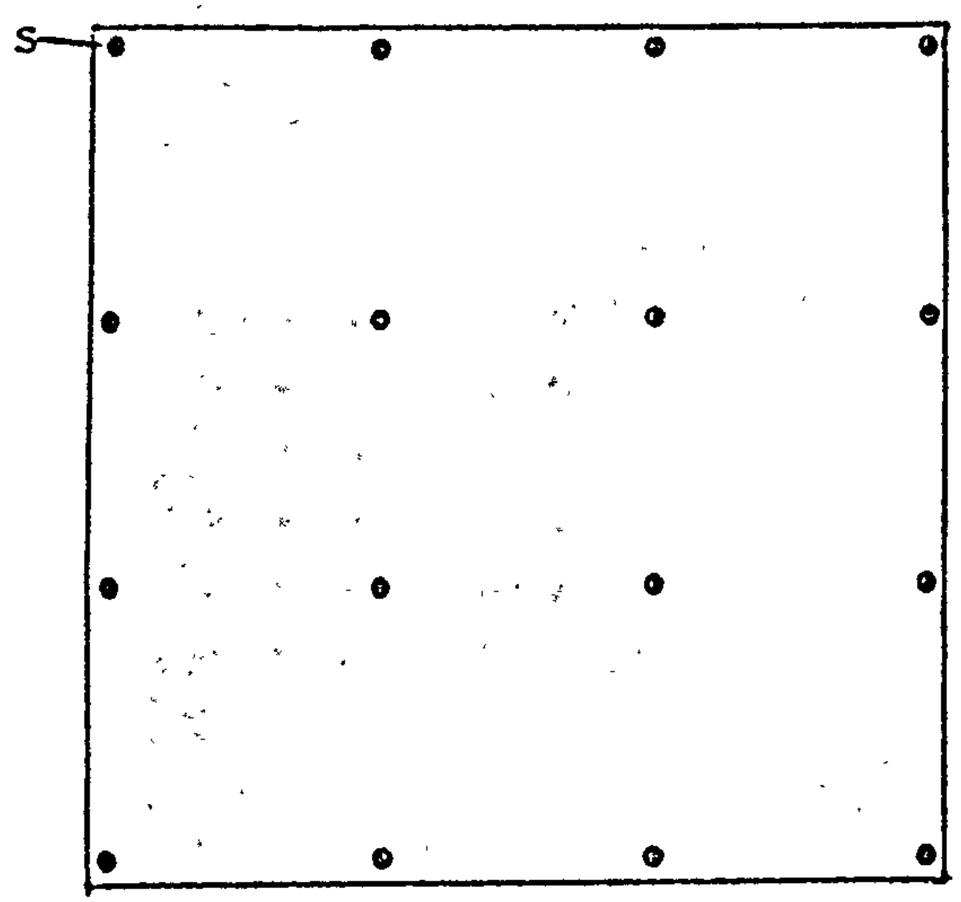
(a) Initial Layout.



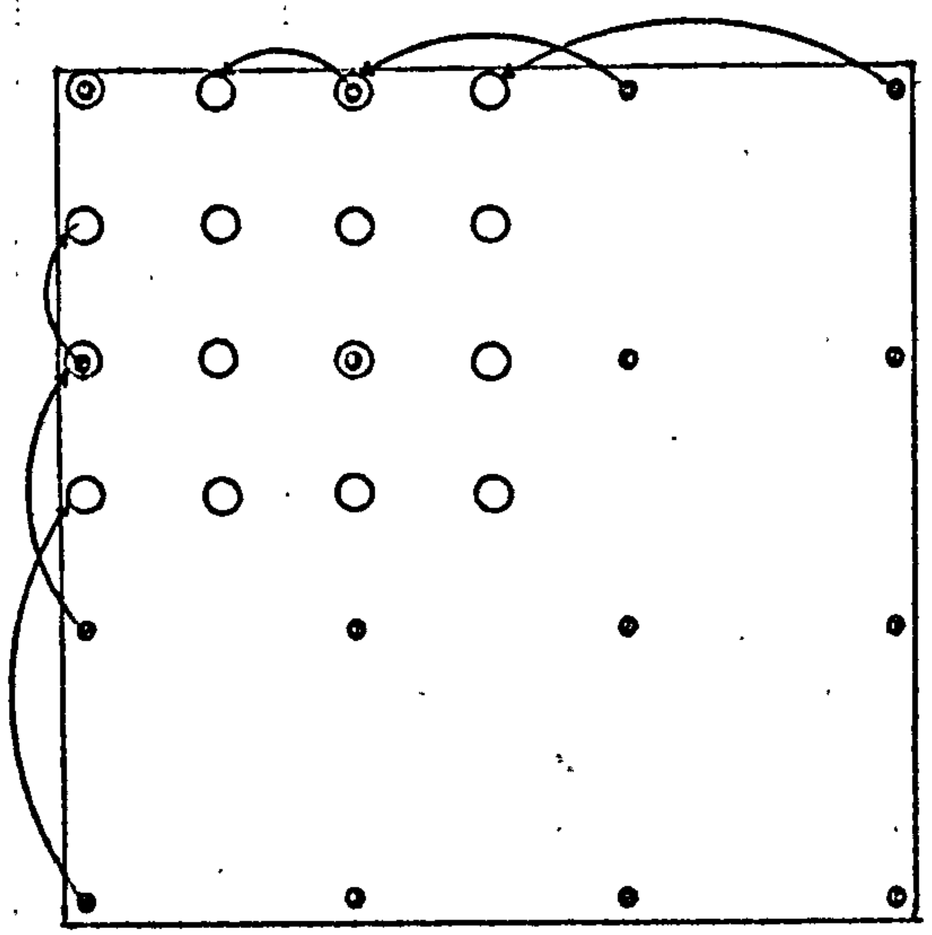
(b) Contraction by two units (one direction).



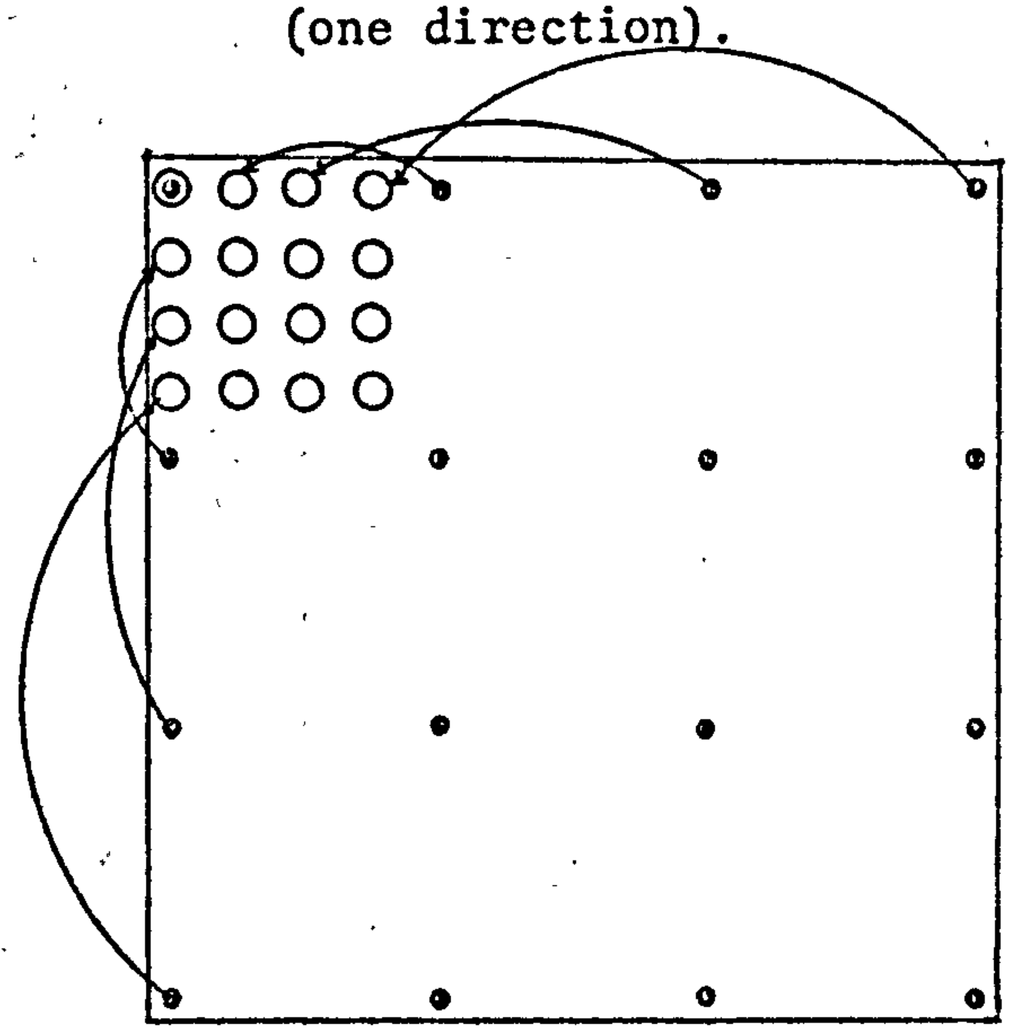
(c) Contraction by three units (one direction).



(d) Initial Layout.



(e) Contraction by two units (two directions).

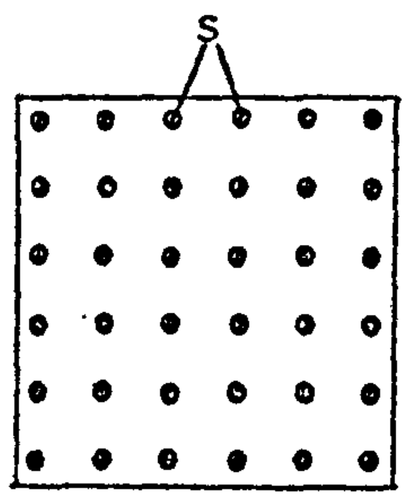


(f) Contraction by three units (two directions).

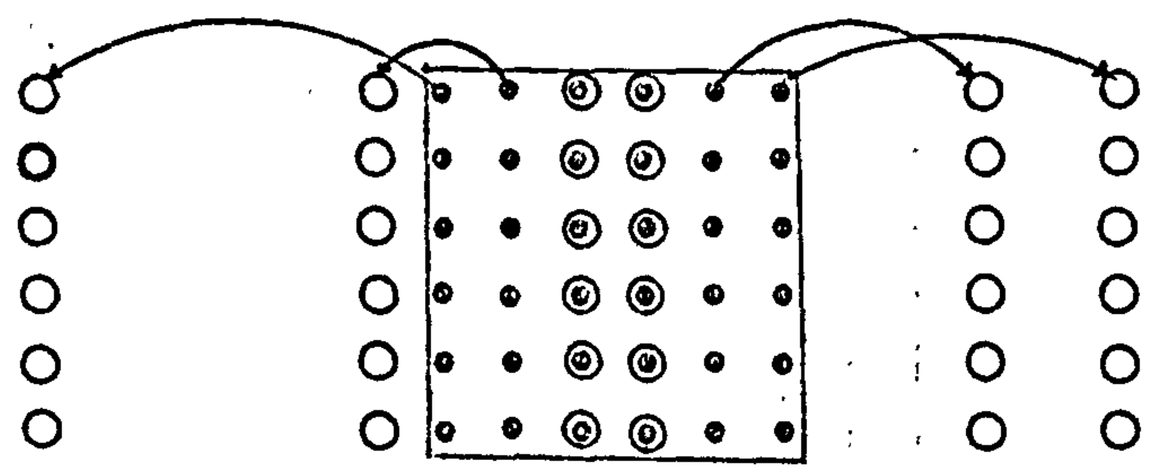
•: Units position before transformation.
o: Units position after transformation.

DIAGRAM 9.4: TRANSFORMATION OF THE SPATIAL DISTRIBUTION OF THE UNITS BY CONTRACTION

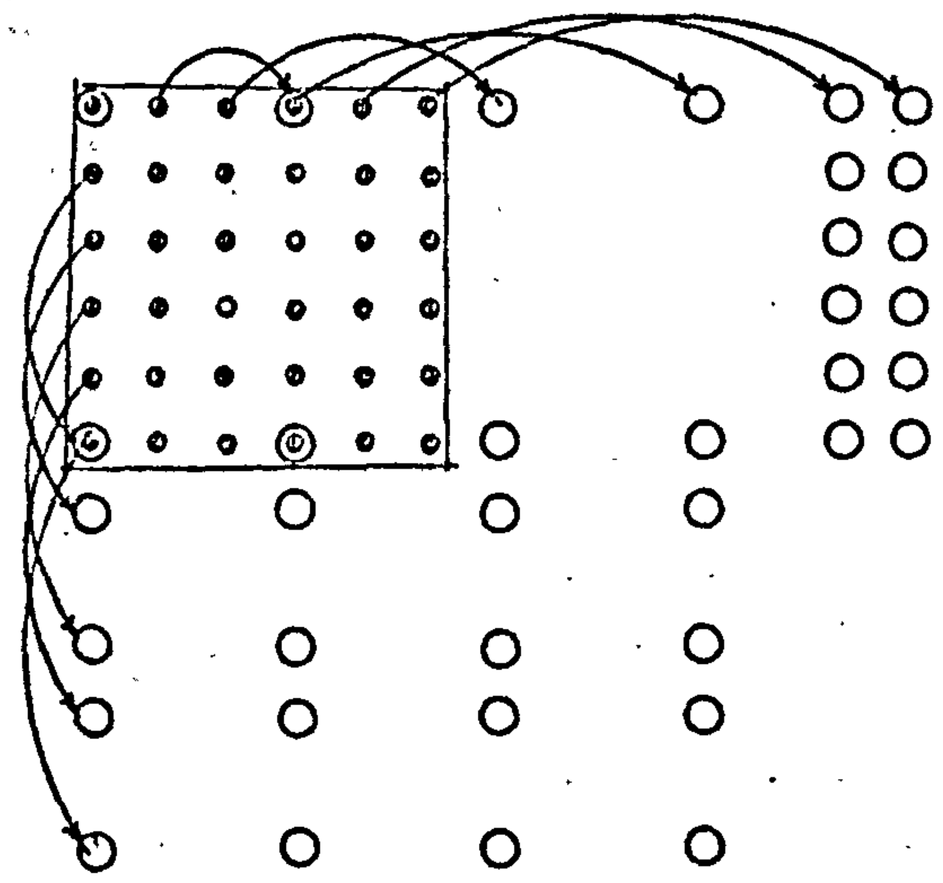
DIAGRAM 9.5: TRANSFORMATION OF THE SPATIAL DISTRIBUTION OF UNITS BY DIFFERENTIAL DILATION



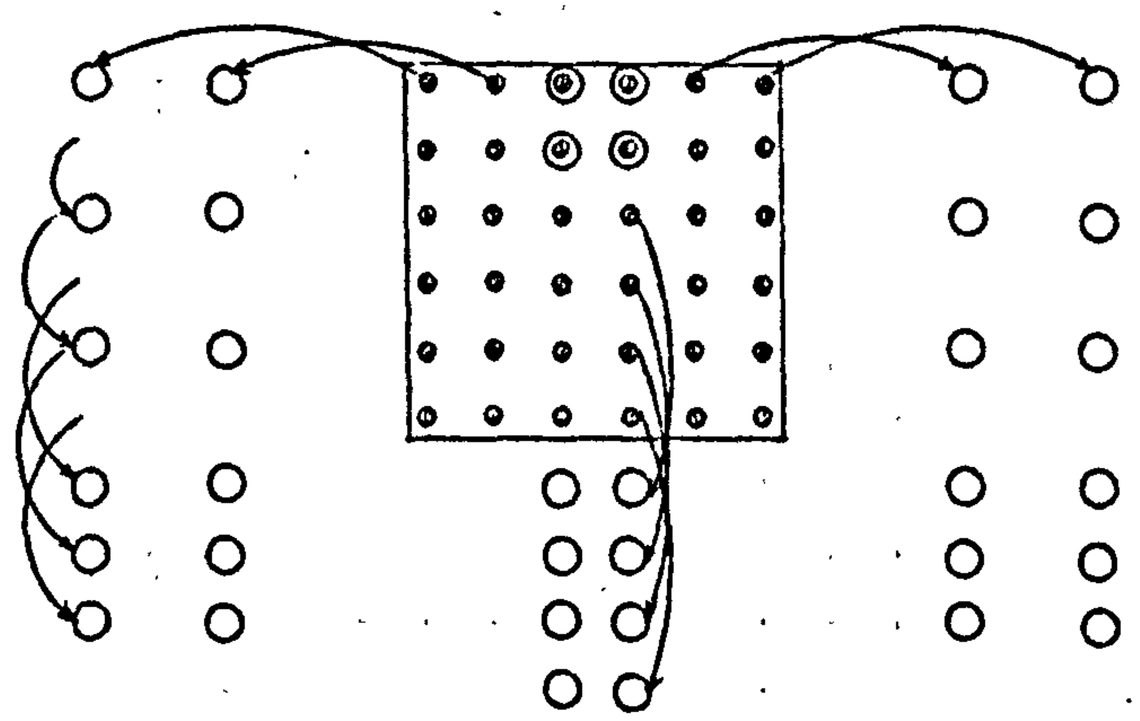
(a) Initial Layout.



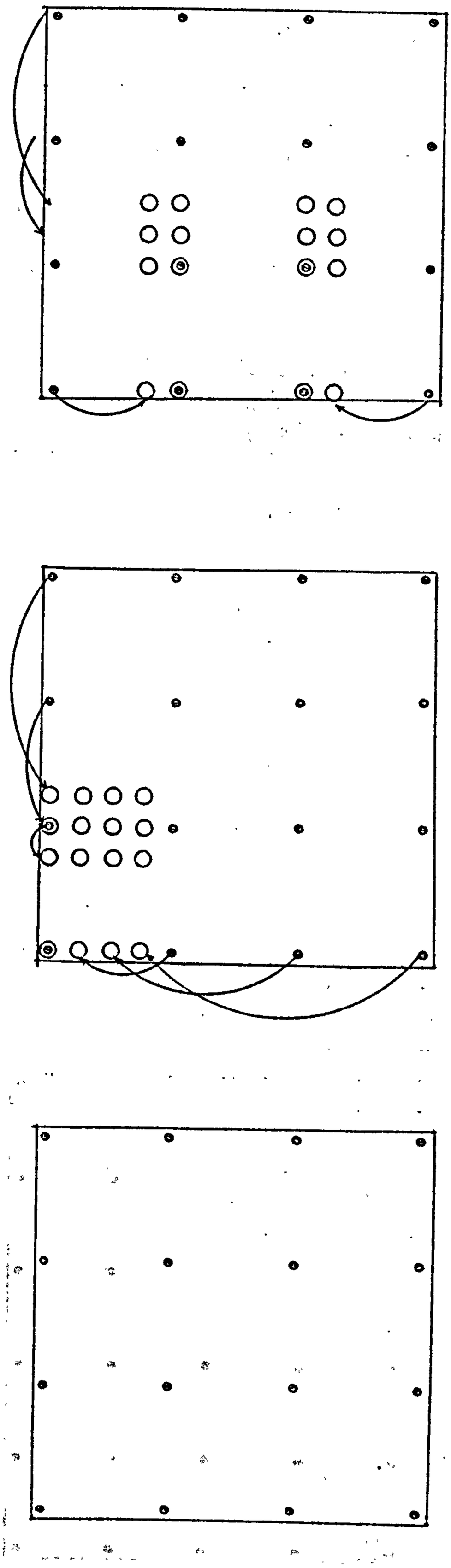
(b) Differential dilation in one direction.



(c) Differential dilation in two directions.



(d) Differential dilation in two directions.

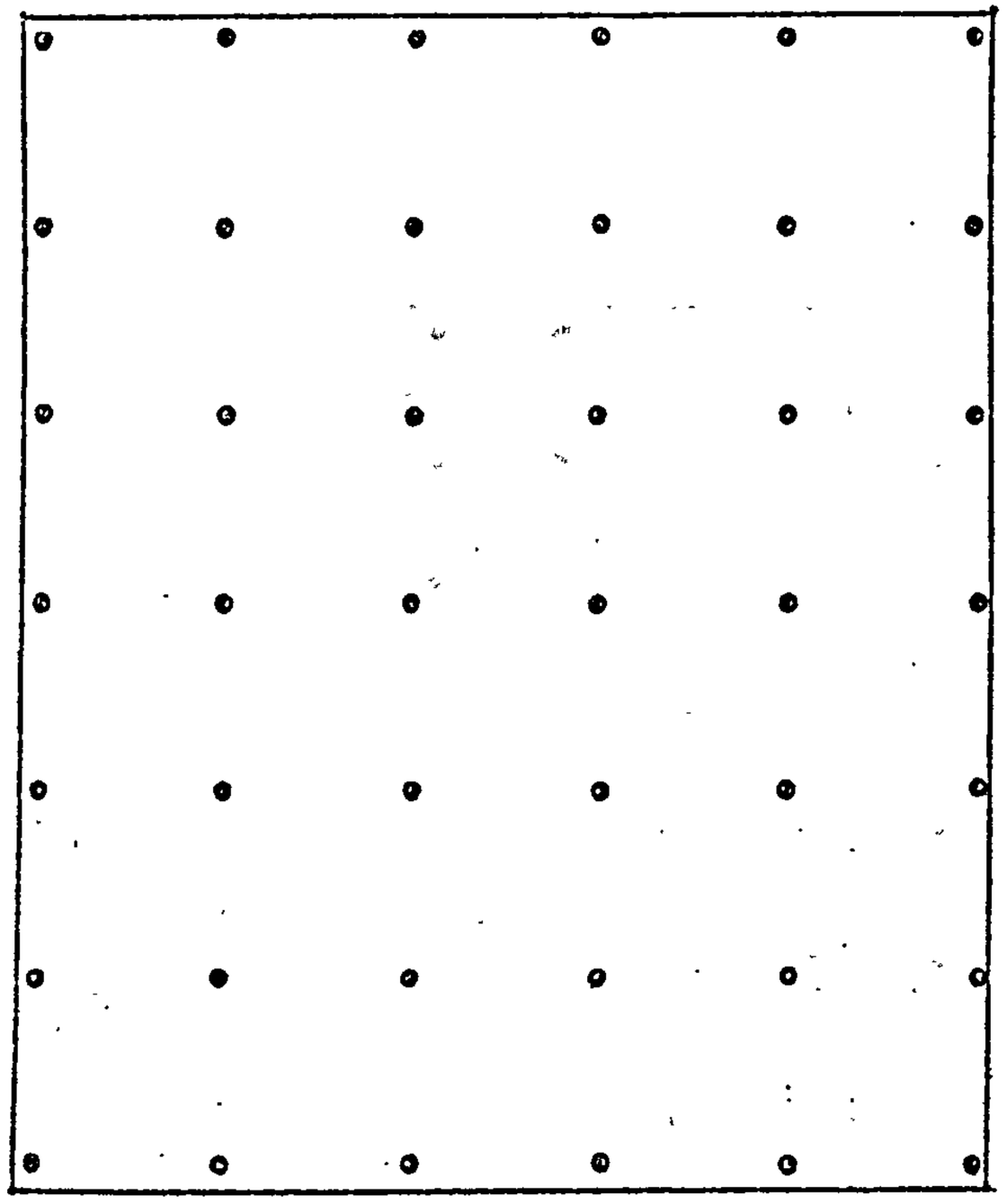


(a) Initial Layout.

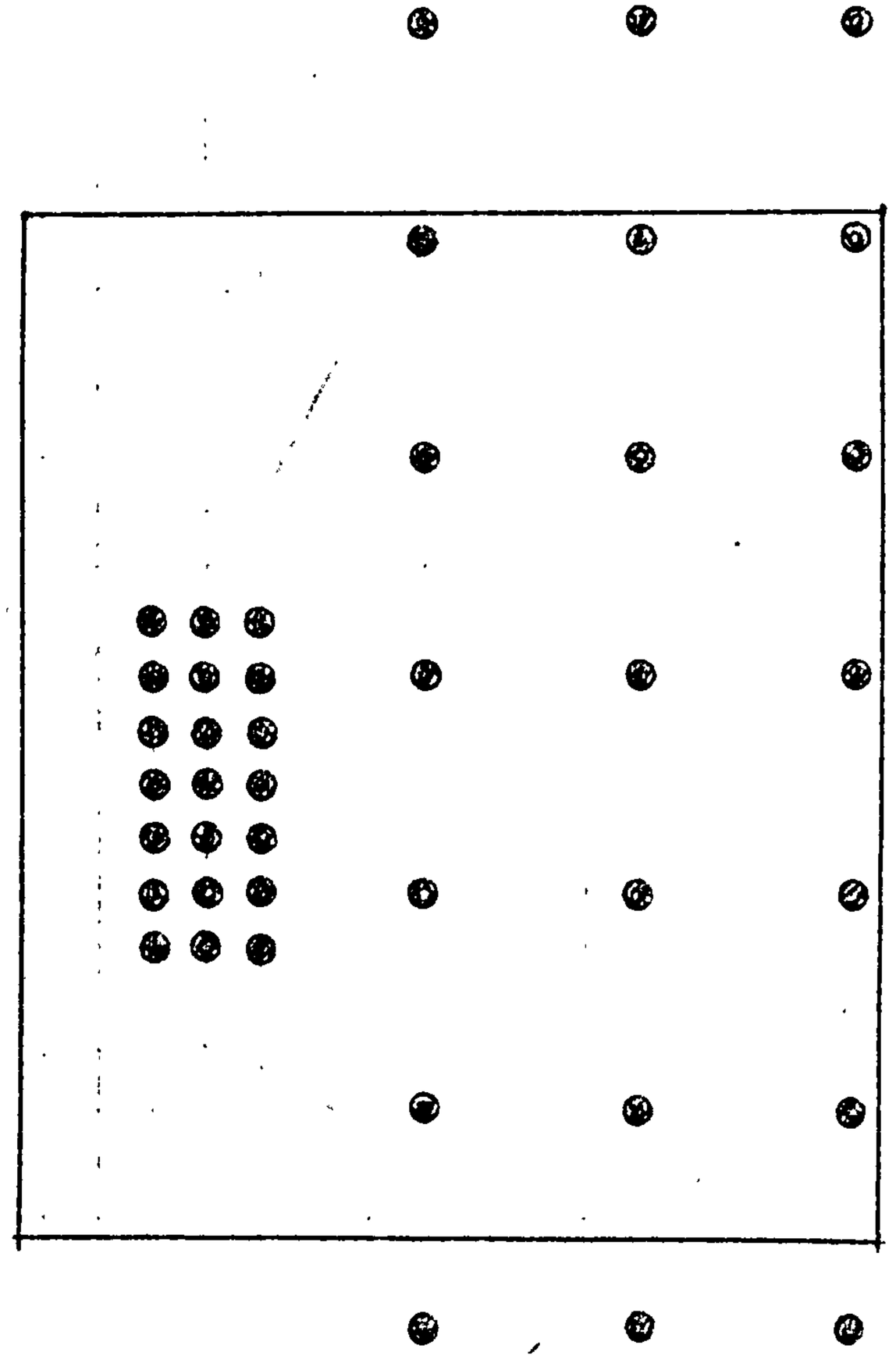
(b)

(c)

DIAGRAM 9.6: EXAMPLES OF DIFFERENTIAL CONTRACTION OF THE SPATIAL DISTRIBUTION OF UNITS

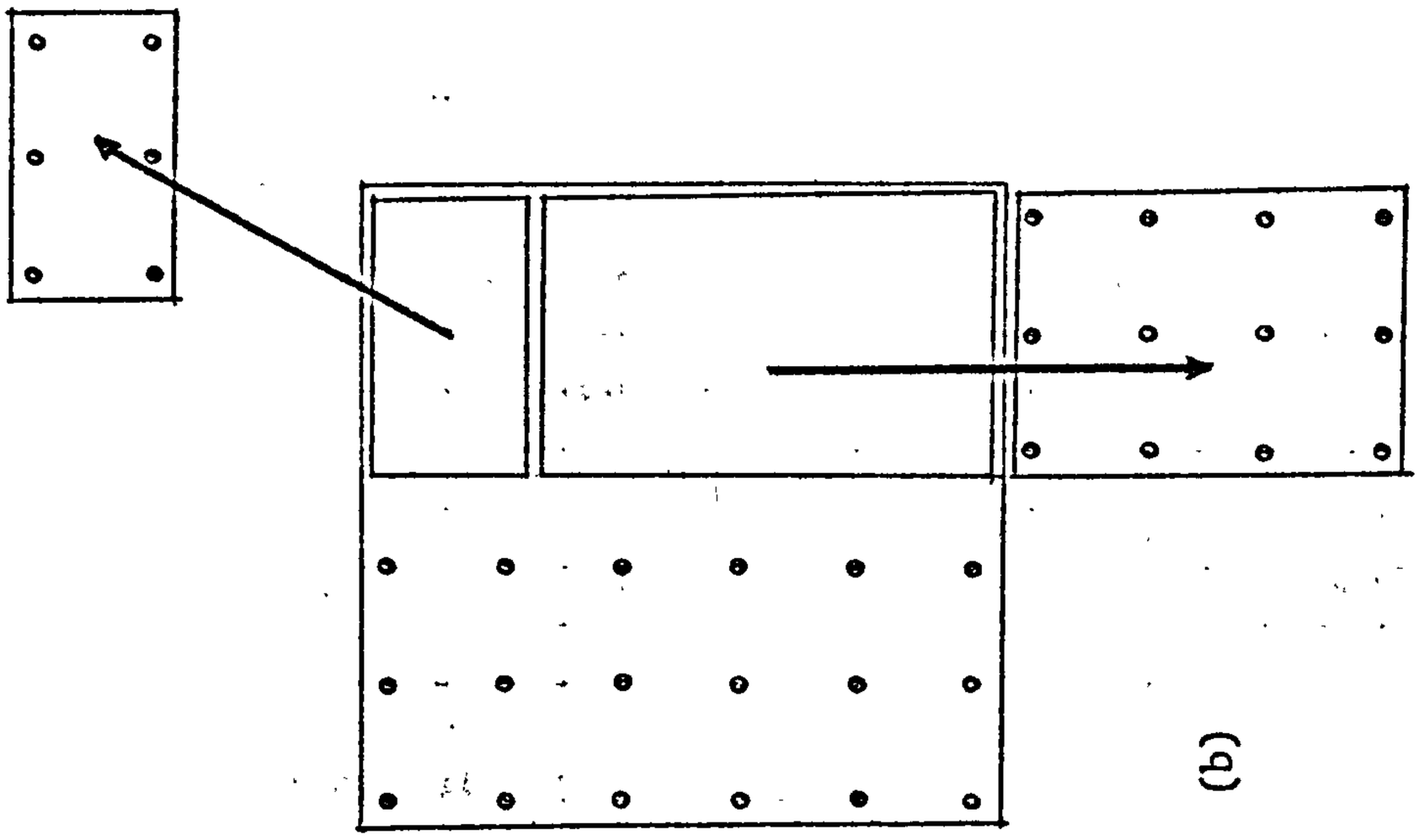


(a) Initial Layout.



(b)

DIAGRAM 9.7: EXAMPLE OF A TRANSFORMATION EFFECTING COMBINED DILATION AND CONTRACTION ON THE SAME INITIAL DISTRIBUTION.



(a) Initial Layout

(b)

DIAGRAM 9.8: AN EXAMPLE OF A TRANSFORMATION OF LAYOUT WHERE WHOLE SECTIONS OF THE DISTRIBUTION MOVE TO NEW RELATIVE DISPOSITIONS

5.12 The above three types of instruction fully qualify the locational operations of the manipulative procedure. In a locational operation there can be a number of transformation intentions, A, and for any transformation intention there can be a number of transformations or extensions, B, and a number, C, of stationary units sets. Denoting the transformation intention by T and the transformation extension by t and the stationary units instruction by S, a locational operation can be described by:

$$L = [T, t, S]$$

and the whole set of locational operations, [L], can be symbolised as:

$$[L] = \{[T], [t], [S]\}.$$

These locational operations act on a distribution of built units given by:

$$\bigcup_{j=1}^{n} (x_j, y_j)$$

By substitution,

$$[L] \rightarrow [B] = \{[E] : [E_+] \subset [E]\}$$

can be written in the more explicit form:

$$\{[T]\ [t]\ [S]\} \rightarrow [\bigcup_{j=1}^{n} (x, y)] = \{[E] : [E_+] \subset [E]\}$$

5.13 Each locational operation produces its characteristic wind conditions and the set of locational operations produces a corresponding set of wind conditions [E]. [E] may be expected to contain the set $[E_+]$ of favourable wind conditions falling in a pre-specified range and described by a measure such as the Environmental Wind Index (chapter VII).

5.14 (c) The importance of the requirement c emanates from the fact that any two or more units situated in proximity to each other create a wind environment resulting from the nature of their spatial interaction. In this respect, a zone of influence can be ascribed to each unit in which

the wind conditions are a result of its form characteristics. As we move away from the unit the influence of the unit on the natural wind field decreases until such a point is reached where the natural wind condition re-establishes itself uninterrupted by the unit. The zone of influence can be used as the spatial datum on which the initial distribution of the units can be based. As a result of contractions through the transformation of the distribution the zones of influence of individual units interact and the resulting wind conditions are determined by this interaction. Therefore, the position of non-interacting zones of influence can provide a good starting point from which the evaluation of the wind condition begins. Inevitably, situations may arise where the size of the initial distribution is larger than the working section of a wind tunnel (if a wind tunnel is used). In such cases one can either reduce the scale of the model, which can be done only to a limiting smaller scale, or start from an initial distribution where the units are very close to each other and dilate the distribution in the transformation process. This will proceed until the limiting size of the working section is reached, and/or, hopefully, favourable E values are achieved.

5.15 Like the accumulative model, the aggregate model emphasises the possibility of a wide choice in a favourable wind conditions range. In so doing, it increases the capacity of a wind generated form to incorporate other design requirements and constraints on the ultimate form.

GENERAL COMMENTS ON THE MODELS

6.01 In both models, it can be seen that the choice of wind relevant form aspects is tentative. This suggests an area of research marked

with desperate paucity of information. Such conceptual models are at liberty to introduce tentative wind related form aspects, but the final test of their validity remains to be achieved empirically. Further, the specification of a range of favourable wind conditions has to be backed with research in wind induced comfort aspects, both indoors and outdoors. The existing criteria of required wind velocities and air changes are lacking in temporal and spatial aspects. Criteria designated to include variations of wind conditions over time and space, as distinct from the conventional average requirement, can well introduce an activity pattern component in the criteria where the time and place of users' activities greatly influence the wind design of built form.

6.02 The models, as stated, are a rule governed design activity, composed of a search methodology with the aid of a wind tunnel or a computer as design tools. They are generative models by virtue of their systematic scanning properties. They may be considered a 'mark 1' form generative models. Their use to study extensive and co-ordinated progressions of form may lead to the establishment of explicit functional relationships (in the mathematical sense) between form and flow. Such relationships will be another generation of wind form-generative models, 'mark 2'. They may be expected to be time saving and can be applied directly without resort to the wind tunnel or the computer. Clearly, the field is far from being anywhere near this, but it remains to be the ultimate objective.

CONCLUSION

Design with wind, at the present state of technology, is time consuming and expensive. This explains partly its neglect in the design of built

form. A comprehensive procedure for design with wind can benefit greatly from a sound conceptual guidance. This was the basis of two design models: the accumulative model based on a unit-by-unit growth of a group form, and the aggregate model, founded on the manipulation of an initial spatial distribution of built units. In both models, the condition of the wind could be monitored and evaluated by a measure of wind such as the Environmental Wind Index. Various wind relevant form aspects can be conveniently introduced at appropriate stages. The models can be used to guide investigation using a wind tunnel or a computer.

Although they are design tools, the models can be used to establish form-flow relationships for an envisaged range of form aspects such that, up to a certain extent, they can be dispensed with once the level of knowledge permits functional relationships between form and flow to be established or a catalogue of forms with their flow properties. At such level, designers can readily use such catalogues or functional relationships to generate their forms.

GENERAL CONCLUSIONS

Design with wind requires the identification and description of the wind aspects that contribute to the quality of the built environment. This thesis has attempted to identify and describe some of such aspects. The relevant design aspects of wind are conceived in its contributive properties of exposure within a space, uniformity of the exposure within it, and its spatial distribution. In search of appropriate descriptors, there is an enormous body of literature in closely or remotely related disciplines which had to be surveyed in order to develop the appropriate descriptive contexts. In relation to the design problem, a morphological approach may prove expedient.

The fields related to the problem of wind and built form are those of fluid dynamics, meteorology and architectural design. On account of the highly theoretical nature of flow description in fluid dynamics, such flow description is inappropriate in relation to the design problem. In meteorology the same theoretical level is maintained with a large degree of adaptation to describe natural wind systems and behaviour. Statistical theory provides a variety of concepts for describing certain properties of natural and social phenomena. It has great potential for supplying useful and fundamental tools for describing the behaviour of wind in built forms. Such tools, however, need to be adapted to meet the particular nature of the behaviour of wind in relation to built form. This adaptation requires the specification of certain criteria of economy in data, sensitivity to changes in form, and to consistency in form/flow relationships.

The concept of an Environmental Wind Index is useful in the morphological study of wind flow and form for the following reasons:

1. it is a concise statement of the properties of flow in rela-

tion to form. The individual measures combined into it, informative in their own right, make comparison between different forms a time-consuming job.

2. it has greater power to differentiate between forms, since it considers qualifying aspects additional to the average shelter.
3. it combines measures whose sensitivity to form, economy in data requirements and consistency contribute in such a way as to suggest that it may be a useful measure of the attributes of wind in form-flow relationships.
4. it unifies individual properties of wind condition into a single statement paralleling the unitary character of the wind field.
5. it is a simple formulation and easy to compute once its component elements have been designated.
6. such a formulation of an Environmental Wind Index has potential for application (probably with slight adjustments and adaptation) in other aspects of the relationship between built form and the natural energy fields of heat, light and sound. Each of these aspects, as occurring in a given designed space, have properties similar to those signified by the measures S (shelter), O (uniformity) and D (distribution). Such a formulation might ultimately lead to a General Environmental Index combining the different elements of the natural environment into a single index, which could be used in expressing overall form-performance relationships and hence in identifying sensitive regions of parameters of built forms.

To ascribe an Environmental Wind Index to a form in a given design situation requires that:

1. a given activity should be specified in terms of the effects

of the wind on its performance and/or comfort aspects (comfort and/or performance criteria).

2. the activity should be spatially well specified, such that the designer has a clear idea about its place of occurrence in relation to built form.

3. the activity should be temporally specified, giving times and/or frequencies of occurrence.

4. spaces defined by the built form should be divided into regions defined by their functional consistency or geometric continuity.

5. the comfort/performance criteria should be expressible in terms of the component elements of the Environmental Wind Index. This condition requires that exposure or shelter properties as expressed in a standard speed of wind should be qualified as to the effect on comfort/performance of the variations and the spatial distribution of the exposure or shelter within the relevant space.

6. the parameters of a built form which affect wind flow should be systematically manipulated over relevant regions of their values in monitoring the behaviour of the Environmental Wind Index until all possibilities are covered or the situation that satisfies the given criterion is reached.

7. the Environmental Wind Index can be ascribed to each region in one of two configurations:

   a) a series of planes

   b) a volume.

   The exposure profile component of the Index, presented visually, may prove a very useful initial medium of comparison between the different regions and forms.

In design with wind a designer can either propose a form which is to be evaluated for its performance or adopt a form-generative approach where the required performance determines the form. The Environmental Wind Index can provide a good basis for a form-generative approach for a continuous progression of form parameters. This is particularly helped by its concise format and sensitivity to flow behaviour.

The Environmental Wind Index may be difficult to evaluate by field observations, but its use in developing designs and evaluating forms in the design process can be of great help for designers. Further, the problem of defining spaces for which an Environmental Wind Index can be ascribed may greatly limit its use as a measure comprising more than one aspect, e.g., a user may be interested only in speeds at the entrance of a building. The cases studied produced relatively simple exposure profiles and the formulation of a localisation factor has been mainly determined by this simple profile. This is an aspect of the Environmental Wind Index which will need further development to deal with the localisation factor in more complex profiles. The Environmental Wind Index as developed here has been concerned only with outdoor air movement. Its application for indoor air movement may require certain adaptations in situations where flow is effected by a thermal component.

Design with wind can be a laborious and time-consuming activity. The economics of the situation may well prove to the the limiting condition on the depth and extent of investigation.

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